“Towards Sustainable Flooring Systems: An Investigation of Novel Materials”

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Ms Dianne Tracy Carter, University of Surrey

Industrial Supervisors: Mr N. Stansfield and Mr J.R. Mantle, InterfaceFLOR

Academic Supervisors: Prof. C.M. France and Prof. P.A. Smith, University of Surrey
Abstract

The aim of this project was to explore sustainability within the flooring industry and in particular from the perspective of InterfaceFLOR, a company with a stated mission to become fully sustainable by 2020. This general aim has been met with specific outcomes that contribute incrementally to existing activities and more radically to the future portfolio of InterfaceFLOR.

Analysis of the flooring industry, considering both the supplier and user perspectives, showed that a variety of requirements are placed on a floor by different consumers in different contexts. This has resulted in a diverse range of flooring materials being produced that fulfil these demands in different ways. Further, it has been shown that revolutionary concepts, considered as part of this project, may be accepted by consumers.

A detailed analysis of the current processing engineering used by InterfaceFLOR in manufacturing carpet backing material was undertaken, with the aim of facilitating the introduction of recycled feedstock. The analysis identified faults with the existing process and suitable modifications enabled the process to be improved and the more environmentally sustainable recycled feedstock to be introduced subsequently.

Since incremental changes alone will only create a more sustainable process, but will not provide a fully sustainable product, the emphasis of the work then switched to the development of revolutionary innovations concepts. During the course of this project InterfaceFLOR has established an ‘Innovations Network’- a group of internal and external experts that has in turn facilitated the investigation of a number of innovative projects. The second half of this thesis describes a proposal and feasibility study of a range of innovative flooring products. This then led to the investigation of a novel resin system (epoxidised linseed oil), based on a renewable material.

The investigation of the resin material has identified the potential use of proxy tests to screen a group of similar flooring materials. The use of proxy tests means that less material is needed and there is the possibility of exploring a greater amount of processing variations in an efficient way. The novel material was shown to perform adequately as a flooring product (compared to existing products) in an investigation which used several analysis techniques, the results of which correlated well with present standard flooring tests and visual assessment methods.
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Chapter 4 Innovation Concept
Glossary of Terms

**Backing** - Fabrics and yarns that make up the back of the carpet as opposed to the carpet pile or face. In tufted carpet:

- Secondary backing - Fabric laminated to the back of the carpet to increase dimensional stability.
- Primary backing - A woven or nonwoven fabric in which the yarn is inserted by the tufting needles.

**Biopolymer** - A polymer that is based on renewable resources and not petrochemicals.

**Bioresin** - A resin that is based on renewable resources.

**Construction** - The manufacturing method (i.e., tufted, woven) and the final arrangement of fibre and backing materials as stated in its specification.

**Cross-linker** - A chemical that has the ability to provide cross-linking of another through the use of atomic bonding.

**Cut Pile** - A carpet fabric in which the face is composed of cut ends of pile yarn.

**Cut-Loop Pile** - A carpet fabric in which the face is composed of a combination of cut ends of pile yarns and loops

**ELO** - Epoxidised linseed oil. An oil produced from the flax plant that is then epoxidised.

**Face-yarn** - The result of yarn tufted through a cloth to form the top-cloth.

**Floor Covering** - This is any covering for a floor such as carpets and rugs and will generally be soft flooring.

**Flooring** - This is divided into two categories- soft and hard. It is defined as structural for the purposes of flammability requirements.

**Fusion bonding** - A method of producing carpet whereby individual short lengths of yarn are held vertical and then secured in place with a primary backing.

**Glasbac** - A patented backing system for carpet tiles manufactured by InterfaceFLOR. It is manufactured from thermoplastic resins, fillers and fibreglass.
Graphlex- A patented backing system for carpet tiles manufactured by InterfaceFLOR. It is manufactured from bitumen, polymers, fillers and fibreglass.

Level Loop- The pile loops of yarn are of substantially the same height and uncut, making a smooth, level surface.

Linoleum- Hard-wearing flooring product made from oxidised linseed oil.

Loop Pile- Carpet style having a pile surface consisting of uncut loops. May be woven or tufted. Also called “round wire” in woven carpet terminology.

PAF- Pour-A-Flor. An innovative concept based on the idea of pouring a floor from a tin.

Pilling- A condition of the carpet face (which may occur from heavy traffic) in which fibres from different tufts become entangled with one another, forming tangled masses of fibres. Pills may be cut off with scissors.

Pre-coat- A coating typically made from latex, used to secure the tufts in the topcloth. It is applied before the backing system.

PVC- Poly-vinyl-chloride. A versatile thermoplastic used in a number of applications.

Renewable resources- Those materials that can be grown and/or created in one human lifetime. This definition does not include materials that have to be mined and they must be easily replaced.

Resilience- Ability of carpet pile or cushion to recover original appearance and thickness after being subjected to compressive forces or crushing under traffic.

Strike-through- A fault in tile manufacturing whereby backing system fluids seep through the pre-coated top cloth and are seen on the surface of the product.

Top cloth- A construction formed by yarn typically tufted through a cloth. However, it can be produced by a process known as fusion bonding or other methods. This is the surface of the carpet that is exposed.

Tufted- Carpet manufactured by the insertion of tufts of yarn through a carpet-backing fabric, creating a pile surface of cut and/or loop ends.

Woven- Carpet produced on a weaving loom in which the lengthwise yarns and widthwise yarns are interlaced to form the fabric, including the face and the backing.
Executive Summary

Climate change and sustainability have become increasingly important issues on the political agenda in recent times. Tony Blair called the climate change issue “probably, long-term the single most important issue we face as a global community” and made it a priority during the UK’s presidency over the G8. In 2005 the G8 summit in Gleneagles agreed to “act with resolve and urgency now” on the issue of climate change (Gleneagles, G8, 2005).

The entire world, developed and developing is now under pressure to consider the effect of their actions and sustainability has become a worldwide issue on the global agenda. Markets for low-carbon technologies are growing and by 2050 could be worth at least US$500 billion (Stern, 2006). There are a multitude of companies that are now using their ‘green credentials’ as a marketing tool. Sales of ‘Fair Trade’ goods increased from £140 million in 2004 to £195 million in 2005 (Department for International Development, 2008) and this market is expected to continue to grow.

A significant part of the global economy is the flooring industry, with steady growth and over US$63 billion sales predicted in 2008 (Freedonia Group Research Studies, 2003). The carpet industry is the largest sector of the flooring market and now worth around US$25 billion (ibid.). The world’s largest commercial carpet and carpet tile manufacturer is InterfaceFLOR (Interface Website, 2007). There is therefore considerable pressure from several sources- both externally and internally on the company to become more sustainable.

The first chapter of this report describes the need for all industries to become more sustainable. There are various methods that are being implemented in order to achieve this, Marks and Spencer for example has its well-advertised ‘Plan A’ (BBC, 2007) and people are making similar more sustainable choices at both work and home. The flooring industry has been tackling this on an individual basis by modifying current products. It has traditionally operated on a take-make-waste scenario and large amounts of material, energy and processing have been required to produce just a few metres of product. InterfaceFLOR is one example of a flooring company that has made constant reductions in environmental impacts by reducing these inputs, whilst producing a consistent product.
In Chapter 1 a review of the service proposition that flooring provides is described. The result of this research indicates that there is a mix of requirements for a floor. Different consumers, segments and areas result in a need for a range of properties for the floor from luxurious to practical, from contemporary to traditional and from fun to subtle. There are many different requirements that consumers place on flooring products.

The social research described in this chapter shows that consumers make strong distinctions between categories of floor and class their purchases as either practical or emotional. Consumers also divide their flooring into temporary or permanent purchases. The way in which a room is used also has a significant impact on the type of flooring considered for that area. The result of this research indicated that there is a mix of requirements for a floor. Different consumers, segments and areas result in a need for a range of properties for the floor from luxurious to practical, from traditional to contemporary and from fun to subtle.

Perhaps as a result of the distinction by consumers between types of flooring it is divided into two categories: hard (smooth) and soft (textile). Hard flooring makes up 35% of the flooring market by value, although it is only 23% by volume (Mintel, 2006). It includes laminate, vinyl, linoleum and PVC tile. Soft flooring, the remainder of the market, includes mostly carpet and carpet tile.

The different categories of flooring are analysed and research is conducted into how the different flooring products fulfil the service requirements. Sustainability within the flooring industry is explored and the way in which these products might fit with InterfaceFLOR’s objectives is considered. It is shown that lessons could be learned from some of the manufacturing techniques currently in use, that could aid the development of a new type of flooring. These include the use of single material products, renewable material, recyclable material (naturally or technically) and low energy in manufacturing. It is concluded that there are no existing products in the marketplace that can satisfy the needs of consumers in a fully sustainable way.

It is also noted that most flooring is not replaced when it reaches the end of its practical usefulness as a flooring product; rather it is replaced for cosmetic reasons. This indicates that the appearance of a floor can be important both in selecting a floor and in use. This research shows that there is opportunity in the marketplace for novel flooring solutions that may be more sustainable than current products, as long as the description of the unique service they offer is well-defined and well-presented.
Chapter 1 describes the Innovations Workshop facilitated by InterfaceFLOR, created in order to assist in the creation and development of innovative ideas. This exercise shows that external persons can be particularly useful in creating a different view on a problem that has been tackled for so long in a particular way. This group also provides expertise that can not be found within InterfaceFLOR. The members of the ‘Innovations Network’ ultimately are watch keepers of the Innovations Pipeline of ideas to ensure that the main purpose of the Innovations Team and the innovations concepts is not diluted.

The results of the workshops and the network are described and InterfaceFLOR now has a different perspective on innovation. The group of innovators—both internal and external will validate the concepts held in the pipeline. InterfaceFLOR has learned through this process that it is not possible to undertake innovation alone. The business needs to support the idea of ‘innovation’ as something which does not have 100% success. Agreement and certainty are not always necessary for these projects as they had been for previous incremental product improvement (Stacey, 1996).

The history of the flooring industry is described in Chapter 2. This enables the background and the scope of the project to be understood within the context of a specialised industry. Current products fulfil consumer requirements that have developed over a long period of time. It can be concluded that the product is not modified because it is important not to change what the consumer perceives they obtain when purchasing a product. The first part of this project therefore continues this general trend in that the current products are considered and analysed.

Flooring products in the market have been extensively tested using strict industry standards, which are in turn controlled by the British Standards, some of which are described in Chapter 2. It is concluded that any new flooring product would have to pass these tests in order to be accepted by the market. However, these tests require a full product to be manufactured for testing purposes. Each time that a product is altered in any way, such as a new face yarn for a carpet tile, the flooring will have to undergo the complete complement of tests.
InterfaceFLOR produces carpet tiles that are evaluated using these flooring tests. For the first phase of this project, in order to help bridge the gap between the status quo at InterfaceFLOR and its ‘Mission Zero’, the current product is assessed. This involves examining the advances already made towards the sustainability goal within the context of processing of the current product. One way of potentially reducing the environmental impact of a product, whilst retaining performance, is to introduce recycled content. This had already been achieved with the availability of recycled face yarn for carpet tiles. Another was identified as introducing recycled feedstock for the filler that makes up a majority of the product by weight. However, the current processing conditions first needed to be refined before feedstock could be altered. This investigation is described in Chapter 3 of this portfolio.

A detailed analysis of the current processing engineering used by InterfaceFLOR is undertaken. It was well-known within the manufacturing process that the ideal line-speed could not be achieved since the carpet tiles could not be cut out of the finished roll at the desired speed. However, a new cutting machine with improved blades were to be introduced which would mean that this were no longer the limiting factor on production. This would then be the movement of filler into the backing system.

The analysis described in Chapter 3 identifies these faults within the existing process and a description of the optimisation of this process is included here. Recommendations are also made for processing conditions; to maintain a consistent flow of material by reducing the amount of material stored in the bunker SB56. The bunker should begin filling when the mass held was below 130kg and stop when the mass held was above 145kg. The agitation in this bunker also aided the material flow when held at a pressure of 0.6 bar and with a ratio of 4.5 seconds, followed by a break of 1.5 seconds. The implementation of these recommendations resulted in a consistent increase in line speed of 25%.

Once the improvements are made to the line, replacement of feedstock can then be considered. Filler is currently removed from a quarry, ground and sieved before being sent to InterfaceFLOR. In contrast, the filler considered for replacement is currently sent to landfill. The purpose of this phase of the investigation is to establish if the two sources could be interchanged and this is described in Chapter 3.
Recycled feedstock is assessed for parameters affecting flow through the processing system such as particle, size, shape and composition. This data will then be combined with the increased confidence in processing and a full-scale trial of recycled material is undertaken. The results from this trial showed that alternative filler could be tolerated if the material was considered inert and the particle size could be held under 300 μm. This result means that the filler feedstock for the backing system is now substituted for recycled material in the process with confidence in the machinery, process and method. This is a clear example of technological alterations that enables the reduction of environmental impact.

As a consequence of this investigation, in combination with the recycled face yarn, the recycled content of the carpet tile produced by InterfaceFLOR could be increased to greater than 70 wt%. The recycled material is now verified by external sources. There are issues with the delivery and availability of recycled material and it may have to be mixed with virgin content in order to achieve the quantity desired. However, the recycled filler has now been launched commercially and will be communicated externally to customers with a guarantee of 33 to 50 wt% recycled content in all product. At current production rates this is over 5,000 tonnes of material per annum being diverted from landfill.

The investigations of flooring service proposition, current products in the marketplace and InterfaceFLOR's current product leads to the conclusion that in order to fulfil its aim to be fully sustainable, the company requires novel concepts. It is shown that it is inherently difficult to be innovative and provide novel solutions when part of a single company. Therefore the process of innovation has been altered within InterfaceFLOR, described in the first chapter. This change in impetus within the company has in turn led to the second phase of this project; the investigation of the Pour-A-Flor (PAF) concept. This concept is described as a biopolymer system that can be poured onto a substrate. The biopolymer would be transparent so that the design from the substrate could be viewed easily. The proposal for this concept is investigated and a feasibility study is undertaken.

In order that the concept can be investigated further the current products and biopolymers in the marketplace are compared against the concept requirements. This is an entirely new concept that has not been described in the literature or patents. The PAF concept is further described and the prototype requirements are defined. A resin material based on epoxidised linseed oil (ELO) was identified as a possible solution to these conditions and investigated further.
A series of experiments, described in Chapter 4, show that the cure time of the ELO-based resin material at room temperature is a major drawback for the PAF concept. However it can be reduced significantly by changing molar ratio and the addition of catalysts. Some catalysts may not be compatible with the need to have sustainable materials and therefore they need to be considered carefully as part of the future investigation of this system.

During the course of the investigation of the PAF concept the ELO-based resin material is identified as potentially beneficial for the flooring market. This investigation spawns a number of alternative concepts that may be fulfilled in the mid-term at InterfaceFLOR and although they are not the final answer to the issue of sustainability, they may provide intermediate steps. Two that are identified are; as a replacement for a poly-vinyl chloride (PVC) tile, Interlock, and as a replacement for the PVC used in the backing system of the carpet tile. The investigation of the material has therefore continued.

Chapter 5 goes some way to describing the environmental impacts associated with the ELO-based resin in comparison with a petrochemical alternative, although a full life-cycle analysis should be undertaken before this system is used commercially, since it should not have any more negative environmental impact that the material it is substituted for. However, it should be noted that a move toward renewable material would be advantageous for a commercial manufacturing process. The ELO-based resin system can also be competitive with the cost of the PVC, provided the same amount of filler is used.

The effects of changing different processing parameters on this material were assessed using a series of mechanical tests and are also described in Chapter 5. The results of this investigation show that the material cures in a shorter time than originally predicted at elevated temperature. The effect of processing parameters on mechanical properties are also observed.

Increasing cure temperature above 150 °C has a slight detrimental effect on properties and a cure time beyond 20 minutes is not necessary for this system at elevated temperature. It is also observed that a molar ratio of Cross-linker: ELO of 2:1 is the optimum for Young’s Modulus and peak stress. Therefore this combination of processing parameters is used for further investigation.
It is still debatable whether a greater Young’s Modulus, peak stress or strain to failure would be more beneficial for a flooring product. The ‘best’ and ‘worst’ samples from the tensile tests are compared using the traditional flooring tests and this is described in Chapter 6. The results show that the ‘best’ and ‘worst’ samples from the tensile tests also produce the best and worst results for the flooring tests. The results of this investigation show that, for this particular type of system with an epoxidised oil and cross-linker, the tensile tests can be used to indicate performance in the flooring tests. This could be particularly useful when investigating other cross-linkers for the ELO as the effect of large number of processing parameters could be investigated, using a smaller volume of material. This means that a greater number of processing conditions could be investigated in a more efficient way. This increases the knowledge of this investigation and the potential use of this system.

A number of flooring tests are conducted on the resin material, both with and without filler. These include the Lisson-Tretrad, Vetterman drum, static loading, stain resistance and flammability. The results show that this material can pass these tests with a similar rating to the PVC Interlock tile.

A number of samples of the resin material are then manufactured for flooring trials, described in Chapter 7. The samples are placed in a high traffic environment for in-situ testing. The wear on the material is observed both visually and through the use of colour measurement. It is seen that there are some trends in colour change that can be observed over the time that flooring is subjected to wear. The results from visual inspection show that the flooring samples perform well in-situ and they continue to be tested. The combination of assessment techniques have similar results and this allows increased confidence in the current visual assessment methods, where it is shown that a combination of experience and training is advantageous.

The complement of tests shows that the material manufactured from ELO and the cross-linker can provide performance under these testing conditions that is comparative to a PVC tile. This investigation shows that this novel resin material can be fit for the purpose of providing a flooring material. The system is also shown to be competitive to PVC as a flooring product in-situ.

Also appended as Volume 2 of this portfolio are the 6-monthly reports that have been completed during the process of undertaking this EngD project. It is suggested that it is unnecessary that the reader will need to read these in full detail in order to understand the research aims and objectives. The research findings and necessary accompanying detail are all contained in volume one.
This project has been divided into two phases as the research has evolved and InterfaceFLOR has developed partnerships for innovation. During the course of this project, the role of the EngD within InterfaceFLOR altered due to a change in the company. The objective of the first phase of this project is to provide the means to environmentally improve current product, in the same way that the company has been progressing in the preceding 10 years.

During the completion of this work partnerships are developed and the ‘Innovations Network’ established. The objective of the second phase of the project is to investigate a novel biopolymer that may have the potential to be a fully sustainable product. This biopolymer is manufactured from some renewable material, which in general will go some way to addressing the environmental issues.

Through the work conducted in phase 1 of this project, the environmental impact of current product is reduced through the introduction of recycled content. This may be reduced further by the use of the product of the phase 2 of this project, ELO-resin as a backing material, the investigation of which is continuing. The PAF concept is expanded and defined. The work also produces a material that may be used as a stand-alone flooring product, with performance competitive to PVC and reduced environmental impacts.
Chapter 1 Overview

1.1 Introduction

Climate change and sustainability have become increasingly important issues on the political agenda in recent times. Tony Blair called the climate change issue "probably, long-term the single most important issue we face as a global community" and made it a priority during the UK's presidency over the G8. In 2005 the G8 summit in Gleneagles agreed to "act with resolve and urgency now" on the issue of climate change (G8, 2005).

The Stern Review in 2006 again refocused attention onto the issue of climate change by highlighting that the poorest countries in the world are those that would suffer earliest and with most catastrophic consequences (Stern, 2006). The G8 had just committed significant quantities of aid to these countries and therefore some of this aid would have to be spent on the consequence of their industrial actions—climate change. The report estimated that by moving the economy on a low-carbon path US$2.5 trillion could be saved. Unchecked climate change could cost the world at least 5% of gross domestic product (GDP) each year; if more dramatic scenarios are considered, the cost could be more than 20% of GDP. Each tonne of CO₂ emitted causes damages worth at least US$85, but emissions could be cut at a cost of less than US$25 a tonne. In summary, quick, decisive action now could have a profound effect on the economy of the future (ibid.).

The entire world, developed and developing is now under pressure to consider the effect of their actions and sustainability has become a worldwide issue on the global agenda. Markets for low-carbon technologies are growing and by 2050 could be worth at least US$500 billion (ibid.). Sales of ‘Fair Trade’ goods increased from £140 million in 2004 to £195 million in 2005 (Department for International Development, 2008) and this market is expected to continue to grow. Sales of hybrid cars in 2006 increased by 23 %, following six years of consecutive growth (Motor Trader, 2007).

Sales of organically-produced food, cosmetics and clothes have increased by 20% since 2007 and now reach £2 billion. Marks and Spencer, Topshop, H & M and Tescos are among the high street chains that have launched organic clothing ranges and the value of this market now exceeds £60 million (The Daily Telegraph, 2008).
An ever-growing number of consumers are buying into the ‘fair trade lifestyle’ and it is inevitable that they are translating this into their business purchases. One such example is the sales of the first carpet tile based on ‘biomimicry’, Entropy, sold almost exclusively to business consumers. Entropy became the biggest selling carpet tile within 18 months of its launch (Stansfield, 2008).

The flooring industry as a whole has had steady growth and there are over US$63 billion of sales predicted in 2008 (Freedonia Group Research Studies, 2003). The extent of this industry is described in the next section. The carpet industry is the largest sector of the flooring market and now worth around US$25 billion (ibid.).

Like every global industry, the flooring industry has been faced with environmental challenges. Some industries have tackled this challenge by providing the same service, but in a different way at reduced environmental cost. For example, Thames Water has been campaigning for people to clean themselves (the service) via the use of a shower rather than bath, thus achieving the same aim with less use of clean water and the associated environmental impacts (Thames Water, 2007). However, the service that flooring provides is not obvious and this is considered in this chapter. Once the service proposition is established, the way in which flooring meets the criteria set out in the proposition can be considered. This is described in Chapter 2. Any innovative and unique flooring that results as part of this project could then be considered in the same way.

The world’s largest commercial carpet and carpet tile manufacturer, who also produce the Entropy carpet tile, is InterfaceFLOR (Interface Website, 2007). Since 1994 InterfaceFLOR has had a ‘Mission Zero’ “to eliminate any negative impact our companies may have on the environment by 2020”. It has historically produced a product in an energy and material-intensive way, described in section 1.3.3. The end product has changed little since the inception of ‘Mission Zero’, as it was considered that change of construction may compromise the performance of the product, which is critical in this competitive industry. There have been incremental reductions in energy required to manufacture, material needed to manufacture, waste produced in manufacture and water required to produce each square metre of product.

This project began in 2003 with a view to continue the incremental progress made towards the goal of 2020 and the prevailing status quo. This began with a review of current processing techniques and an assessment of evolutionary progress already made to become a more sustainable company. During the course of this project the emphasis switched to the development of revolutionary innovations concepts. The second half of this thesis describes an investigation into an innovative flooring product that may fulfil the needs that are set out in this chapter.
1.2 The Flooring Industry

1.2.1 Background

The flooring industry was worth over £2 billion in the United Kingdom (UK) alone (Mintel, 2006). This value excludes accessories such as fitting costs, floor preparation and underlay. 65% of this figure is spent on carpets and rugs, whilst the remainder is spent on smooth flooring, which includes laminate, linoleum, vinyl, ceramic tiles and others.

The flooring industry has traditionally been closely connected to the health of the economy. This is because in times when the economy is less buoyant, there will be a less buoyant housing and office market. This will result in a lower need to redecorate recently vacated premises. Flooring is also something that is often more easily be compromised when economising is required, as there will be less investment in refurbishing premises and homes. Therefore the flooring market has been particularly reliant on the economic performance of other industries (ibid.).

Currently the flooring market is steadily growing and the value of the market has increased by 5.3% since 2001 (ibid.), despite a decline in volume from 2005 to 2006, mostly due to the slow-down of the UK economy. In 2006 it was estimated that 170 million m² of carpet and 54 million m² of smooth floor coverings would be sold (ibid.).

Until recently, carpets were the preferred flooring for UK households. However, since the 1990s, low-cost laminates have been making enormous gains in the market, with a 40% increase in value from 2001 to 2006 (Mintel, 2006). Some consumers are reporting bad experiences with laminate flooring such as poor sound insulation, heat insulation, wear and cleanliness and are being driven back to carpet. The carpet industry is therefore making some value gains and is now showing signs of recovery.

This recent switch in the types of floor that are specified has shown that consumers are now more willing to experiment with their choices. This may be as a result of the home-makeover style programmes that show the variety of options available to those that wish to be more creative in their home environment (Narotzky, 2006).

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1 Mintel Research is a global supplier of consumer, media and market research. The company has been in business for 35 years producing tailored reports, business and rival intelligence through thorough market analysis. It is internationally recognised for its market intelligence and produces over 600 reports per annum.
The flooring market is varied and extensive and has grown out of a need to satisfy a practical purpose, which has since developed into more complicated requirements. These are described here in order to understand how the industry has developed and become so large and varied.

1.2.2 Flooring Requirements

Consumers make strong distinctions between categories of floor (O’Neill, 2003). They divide flooring into permanent and temporary. Those that would be considered permanent are more costly materials such as wood and ceramic. Temporary floor coverings would be those such as vinyl, laminate and carpet. Consumers also see the buying process as either practical or emotional. Practical choices would be laminate or vinyl and those emotional choices may be hardwood and ceramic.

These practical and emotional requirements are problematic to assess without a great deal of social research. InterfaceFLOR commissioned Ibbotson Research and Planning to research the requirements of flooring from a customer point of view (Ibbotson, Research and Planning, 2004). The aim of the research was to understand, explore and test theories with respect to how different consumers regarded their flooring needs. This research took the form of extended focus groups with home consumers and telephone interviews with ‘specifiers’- those who specify which type of flooring will be used in commercial premises.

The group of ‘specifiers’ is small and their choices depend largely on their role within the supply chain, which may be as an architect, designer, flooring contractor or end user. InterfaceFLOR sells largely to these types of individuals through well-established relationships. In section 1.1 the success of the Entropy carpet tile was discussed along with the influence of the ‘fair trade lifestyle’. It is suggested that the ‘specifiers’ make similar choices for their homes and businesses as they try to incorporate their own values in these decision-making processes.

Although some of the groups were attended and personal observations taken, the Ibbotson, Research and Planning report is summarised.

Five extended creative focus groups of consumers were segmented according to lifestyle. The consumer groups were homeowners who made their own decisions on their home décor. They were a mix of gender, ages and economic group who lived in a range of properties (age and type). The focus groups were divided into the five consumer group life stages: young singles who were professionals, those who had partners and no children (DINKies), young families, older families and empty nesters (those whose children had left the family home).
The focus of the groups was to establish the current flooring throughout their homes, related motivations for purchase and satisfaction levels. There was also an attempt to establish what emotional and functional factors have to be fulfilled by each flooring material to meet the needs of different rooms.

Creative stimulus was provided to establish what inspired the consumers and what characteristics make up the perfect flooring. This was provided in the forms of items and images and the consumers were asked to pick ones that inspired them in some way with the brief of creating the perfect flooring for a given room. The items included bubble wrap, soft cloth material, stones and mirrors.

The results of the investigation show that each group of homeowners had different emotional attachments to their flooring. For example, the empty nesters tend to prefer traditional products to suit their older properties such as quality carpets, ceramic tiles and vinyl tiles. They sought familiarity, value for money and functionality.

Older families again tend to have older, larger homes with natural materials a heavy feature of their flooring- wood and stone tiles in particular. Carpets were very popular with this group.

Young families were generally situated in traditional semi-detached or terraced housing. They had a variety of flooring from traditional carpets throughout the home to laminate, ceramic tiles and some carpet tiles.

DINKies had a range of home types, with carpet remaining very popular. Wooden floorboards were also popular, along with stone or quarry tiles.

Singles lived in smaller homes such as flats or terraces with original features like floorboards or carpets. They were the group most open to a variety of flooring such as coir, stone, wood, laminate, tiles and linoleum.

This initial survey showed that there were distinct differences between the ways in which each group furnished their home. Each group had a different relationship with their flooring. As the groups got older they expected more luxurious flooring that was more durable. The younger groups tended to prefer to experiment more with their flooring choices and were more likely to go for the less expensive options. Therefore age is as much a factor as lifestyle in determining preferences.

This may be reflected in the recent boom in laminate flooring as those younger families have purchased more flooring as they enter the housing market. This is discussed further in the next chapter.
The reasons behind the decisions made with choosing flooring were also examined. These showed that the empty nesters had high disposable incomes, but they were careful spenders - they wanted value for money. They also required flooring with little or no DIY and little maintenance. Their priorities were comfort and texture.

Families were divided by their income more than the age of their children. The lower income families preferred mass-market products, whereas those with more income desired luxury, design and texture. Ease of clean and functionality were still important to both.

DINKies preferred designer and innovative products, they were therefore more likely to lead trends, or follow quickly. They had limited constraints on their choice of flooring and were more likely to spend more.

Singles were style conscious, but aware of the age of their house and the way in which natural materials such as wood could be used within this environment. They generally had a lower income and therefore constraints did exist. They were not typical users of carpet.

The creative stimulus also showed how open these groups were to new ideas when asked to give ideas for their perfect room. Firstly they were asked to describe the function of the room. These are summarised below.

Kitchens:

- Durable, waterproof, sealed and easy to clean
- Less of a need/desire for texture
- Concerns about dirt trapping and hygiene
- Likelihood of barefoot walking
- There should be a consideration of users - children, pets etc
- “Industrial floors” are emerging as a popular choice
- Laminates and vinyl remain popular

Dining Rooms:

- The requirements depend on design and function - a separate room for evening/formal occasions is very different to an open family room used 3 times a day for 7 days a week
- A room that is more formal tends to have the same demands as lounges
- A more functional room tends to have the same demands as kitchens

Lounges
• Texture and comfort is vital for most consumers in the lounge
• This is the showpiece room and therefore high quality is required
• Carpets are more popular in this room but wood in combination with luxurious rugs are also popular

Conservatories:

• The needs of a conservatory depend on the purpose
• To relax, to play or to dine
• It is considered an extension of the family room, dining room or lounge
• Flooring will typically reflect what is used in these connecting rooms- a continuation of a theme

Utility rooms:

• These are similar to kitchens- they are more demands for impermeable material which makes some consumers nervous about modular flooring

Bathrooms- There are two schools of thought for bathrooms that are very distinct:

• Impermeability, which tends to be more in child and male dominated households. This results in a more quirky and design-conscious choice
• Texture, which tends to dominate in adult only households or en-suite bathrooms. Consumers are looking for a more luxurious feel

Bedrooms:

• The master bedroom is considered to be emotionally a cocoon and therefore soft, warm textures are preferred. It is in this room that the consumer retains the most emotional attachment to the floor. Lino and modular flooring is far less common in this area with wood and laminates rarely featuring
• The children’s bedrooms tend to be carpeted, with innovative, quirky designs more common. As this area frequently doubles as a play area consumers are more open to modular flooring here
• Guest bedrooms follow similar lines to the master bedroom- but on a lower budget

The Home Office:

• This is more a functional room
• There is less texture but it does tend to mimic the surrounding rooms, hall or landing
Play Rooms:

- It is rare in the UK that there is the luxury of space to have a play room
- If there is a separate area it is often open to all sorts of possibilities with different textures, designs and colours
- It needs to be safe, bright and stimulating

Halls and Landings:

- These are high traffic areas and therefore the flooring needs to be durable, hard-wearing and easy to clean
- This area is viewed as the ‘face’ of the house and therefore needs to be in line with current design trends
- Carpet is still very popular in this area, in line with the need for texture and softness, particularly upstairs where it connects with bedrooms and bathrooms

This research shows that there are distinctly different requirements for different consumers and different areas of the house. The requirements of flooring cannot be generalised to a particular set of values. There is more emotional attachment to flooring in particular areas of the home, whereas in others practicality takes precedence.

The creative stimulus was used to draw out phrases about the perfect rooms for each segment. For example, the perfect kitchen was described by the empty nesters with words such as soft underfoot, hardwearing, practical naturals and colour. In contrast the young families chose words such as practical, safe and subtle. The young professionals chose a mix of materials and suggested phrases like bold, fun and contemporary.

This research showed that there was a mix of requirements for a floor depending on life stage and situation. Different consumers, segments and areas resulted in a need for a range of properties for the floor from luxurious to practical to safe to funky, fun and contemporary.

It could be concluded that although people do not often consider the floor an important part of their lives, it does provide some social value and they consider that it can add economic and aesthetic value to their homes.

In recent years there have been greater concerns about the environmental impact that any product can have and the flooring industry is also affected by this concern.
1.2.3 Environmental Concerns

The flooring industry has traditionally operated on a take-make-waste scenario. There can be significant volumes of material and large amounts of processing required to make just a few metres of product. For example, in the carpet industry the yarn can be manufactured from petrochemicals, via extrusion, then punched through a petrochemical-based cloth, backed several times and then distributed to the consumer. This is shown schematically in figure 1.1.
Figure 1.1. Schematic life cycle of flooring product
Flooring is something that can be in place for several years and often the consumer has little idea of where the flooring originated from when the time comes for disposal. By default, the disposal of flooring then often becomes the consumer’s responsibility.

In order to satisfy the practical concerns of the consumer the flooring industry has been producing more resilient flooring with claims of longer durability. One such example is the linoleum industry that has been usurped by the vinyl industry (Sarin, 2005), which is described in the next chapter. There are other examples where material has been replaced in order to provide a ‘better product’ and as a consequence there have been enormous environmental disbenefits such as the replacement of wool with nylon in the manufacture of carpet, described in the next chapter.

Most carpet is not worn out in its lifetime and is replaced for reasons other than destruction of the material. The colour can become outdated, the room may be redecorated or the carpet becomes discoloured through spills and excessive cleaning. 70% of carpet is discarded for these reasons and could be re-coloured to extend the lifetime in service (Color Your Carpet, 2006). Sections of discoloured carpet could be selectively re-dyed in-situ without having to remove and replace the entire floor. In the US annually 800 million square yards of carpet are land filled, of which little can be recycled easily (Weiss, 2003). However, down cycling is often used, as previous carpet becomes the filler for a new carpet backing. Incineration is an option that may recover some of the intrinsic energy in the product, but is often not a socially acceptable alternative (Duchin and Lange, 1998).

Although it has been noted that there may be more environmental impacts than ever associated with choosing a floor, it is also worth noting that some industries are working to address these challenges. An example of a company that is trying to reduce their impacts is InterfaceFLOR who will be discussed in the next section. Since InterfaceFLOR is a carpet-tile manufacturer, the industry within which it works will first be described.

1.3 The Carpet Industry

1.3.1 Background

The carpet industry began with the weaving of Egyptian cloth around 4,000 years ago and was worth around US$25 billion worldwide at the mill level annually in 2001 (Carpet and Rug Institute, 2001). £3,016 million of carpet was sold to consumers in the UK alone in 2006 (Mintel, 2006).
Carpets will be essentially composed of face yarn, primary backing, a bonding compound and often a secondary backing. This is shown in figure 1.2.

![Typical cut pile carpet profile](image)

**Figure 1.2. Typical cut pile carpet profile (Carpet and Rug Institute, 2003)**

There are many types of construction that are used to create the face yarn, which may also be manufactured from different materials. Usually fibres are pushed through a primary backing and secured to form the top cloth. The proportions of materials and the method of construction have changed considerably over the life of the industry and the most recent figures available are shown below.

![Carpet manufacturing in US by square metres](image)

**Figure 1.3. Carpet manufacturing in US by square metres (Carpet and Rug Institute, 2003)**

Tufted carpet styles are the most popular carpet type and range from loop, cut pile, and combinations of cut and loop. They often offer different pile heights across the carpet that results in different patterns within the carpet, as different colour threads can be made prominent. Stepping or zigzagging using individual needle bars is used to achieve this. The different manufacturing methods are described in greater detail in Chapter 2.
There are different reasons for choosing particular material fibres as face yarn. Nylon is used in a large percentage of carpet applications as it offers low cost, good wearability and abrasion. If it is solution-dyed then it is generally resistant to the harsh chemicals used in industrial cleaning treatments and is more suitable for hard-wearing applications.

Olefin (polypropylene) offers an excellent water-vapour barrier and so is easily cleaned. It again offers good wear-resistance because the colour is added to the fibres during production and is inherent across the entire fibre.

Polyester offers a luxurious feel and so is used in thick-cut pile textures. Wool offers similar properties, but because of its historical significance it is known as a luxury material. Both are generally soft to the touch, but require a high bulk fibre density in order to achieve good wear properties (Carpet and Rug Institute, 2003).

The top cloth is that which provides the design and colour that a consumer will see. It also provides the wear and durability as it is exposed as the top surface. However, the other parts of the constructed carpet also have function. The secondary backing will provide dimensional stability during use as well as bulk, essential in installation. It also secures the structure of the carpet in place. This is further described in the next chapter. These processes are energy intensive and use material that is mostly not sustainable. The carpet industry is trying to address these challenges that are now being presented and this is described in the next section.
1.3.2 Environmental Concerns

The Carpet and Rug Institute (CRI) concedes that “There is no question that the manufacture of carpet is an intensive industry process, requiring substantial consumption of water and energy. There’s also no question that the disposal of post-consumer carpet has been of increasing environmental concern” (Carpet and Rug Institute, 2007).

It is clear that the industry is itself concerned with both the manufacturing process and the materials used in the construction of carpet. The materials listed in the above section, with the exception of wool, are mostly unsustainable as they are sourced from petrochemical supplies. It is clear that these supplies will run out in the future, although there are dynamic debates as to when this will occur (GAO, 2007, Duncan, 2000).

Although the carpet-industry is material, energy and water intensive, it has been making steps to reduce these impacts. For example the CRI reports that

“Over the last dozen years, water consumption at the mill level has decreased by 46 percent. Since 1995 alone, mills have reduced the amount of water used by almost 54 percent. Innovation and conservation has allowed some mills the ability to save as much as 22,000 gallons of water per day to process each 1,000 square yards of carpet. From 1995 to 2002, the industry on average reduced the amount of water needed per square yard of carpet from 14.1 gallons per square yard to 8.9 gallons per square yard. This comes at a time when industry production also grew about 42 percent over the same time period” (Carpet and Rug Institute, 2003).

Each process in carpet manufacture relies on a large input of energy and raw materials. Occasionally in some carpets, the backing material is made from natural or recycled materials such as jute, but generally the main constituents are all petrochemical-based. This has only been the case since about 1954, when up to that time cotton was the only fibre used in tufted products (Carpet and Rug Institute, 2008). With the explosion in the petrochemical industry, nylon offered competitive performance at reduced cost and therefore tufted products, which are simple to produce in nylon, came to dominate the market.
There have been numerous attempts to deconstruct carpet at end-of-life in order to facilitate easier recycling of the constituents, recover embodied energy and therefore reduce environmental impacts. Collins and Aikman (U.S. Patent, 1997) operate a production-scale operation that claims to be able to recycle any vinyl-backed carpet 100% into a 100% recyclable product. It involves extruding and calendaring reclaimed carpet into new backing. The finished carpet contains a minimum recycled content of 30 wt% overall. However, the remaining 70 wt% is still virgin material and has the associated energy impacts.

One carpet-tile manufacturing company in particular, InterfaceFLOR, has become well known for trying to tackle the sustainability issue. InterfaceFLOR will be described in the next section.

1.3.3 InterfaceFLOR

1.3.3.1 History

In 1973 Ray Anderson founded InterfaceFLOR as Carpets International Georgia. InterfaceFLOR has a 40% market share in carpet tiles globally. It has 29 manufacturing sites across four continents, with sales and manufacturing in over 30 countries, selling to more than 110 countries worldwide. InterfaceFLOR directly employs over 6,000 people across the globe (Interface website, 2007).

In 1995 Interface Inc., as the company was then known, sold US$802 million worth of carpets, textiles, chemicals, and architectural flooring. In order to achieve this, the company, along with their suppliers “extracted 2.69 million tonnes of material from the Earth’s stored natural capital. Of this, 880,000 tonnes was relatively abundant inorganic material, mostly mined from the Earth’s crust and 1.76 million tonnes originated from petrochemicals. Roughly two-thirds of these petrochemicals were burnt up in order to convert the remaining third and the inorganic material into products” (Anderson, MCC, 1997).

In 1994 Anderson set out his vision of sustainability for the company he founded in 1973. He challenged his associates “to be the first company that, by its deeds, shows the entire industrial world what sustainability is in all its dimensions: people, process, product, place and profits- by 2020- and in doing so we will become restorative through the power of influence”. Subsequently InterfaceFLOR has called this ‘Mission Zero’.
Ten years after setting Mission Zero, sales at InterfaceFLOR, stand at around US$1 billion, an increase of 25%. In terms of environmental impact, despite this increase, carbon intensity is down by a third, greenhouse gases are down by 46% in absolute terms, and over the same period water usage has been reduced by 78% per square metre of product (Anderson, 10th Anniversary message, 2004). InterfaceFLOR has therefore made considerable progress in addressing its environmental issues.

1.3.3.2 Sustainability Progress

Since the inception of ‘Mission Zero’ InterfaceFLOR, has focused on reducing waste, reducing water usage, reducing energy requirements and the use of 100% renewable energies throughout the UK, in line with global achievements.

InterfaceFLOR, Europe has made similar progress to InterfaceFLOR, global, in tackling the seven fronts of sustainability as it has defined them:

- Eliminating waste
- Having only benign emissions
- Using renewable energy
- Closing the loop to use recycled or bio-based materials
- Using resource-efficient transportation
- Sensitising stake-holders
- Redesigning commerce

Life cycle analyses (LCA) show that the large amount of processing is an important factor in the environmental burden of the carpet tile, although it is dwarfed by the environmental impacts of the petrochemical-based materials (InterfaceFLOR, LCA, 2003). This LCA included the following:

- Extraction, production packing and transportation of raw materials for the product
- Energy, waste, emissions, packaging, transport and installation of the product
- Use of the product (vacuuming and shampooing)
- Disposal by landfilling at end of life (typical scenario)

Examining the global warming potential (GWP) only, the distribution of impacts is shown in figure 1.5. Here GWP is defined as “the release of gases like carbon dioxide, methane and CFC’s (chlorofluorocarbon’s) which contribute to global warming by absorbing reflected radiation from the earth’s crust” (ibid.)
It can be seen from Figure 1.5 that the majority of GWP arises due to the use of virgin raw materials. Nylon contributes 8.01% to the total embodied mass, but 38.36% to the total embodied energy and 49.27% to the total GWP. PVC in the backing system contributes 9.97% to the total embodied mass, 24.94% to the total embodied energy and 7.14% to the total GWP. The total embodied energy is defined as “the amount of energy contained in the material and the energy required to manufacture the material” (ibid.).

It is sensible to consider reducing the environmental impact of these materials via their replacement, such as with those from renewable resources or recycled material. However this would have to be considered carefully to ensure that there will not be significant contributions to other impact categories. For example, recycled glass has greater overall environmental impact than a new Tetra pak container, due to the increase in associated transport costs and energy required for the recycling process (Cowell, 2005).

It is also worth noting that some attempts have been made at reducing the amount of material required to produce the same quality product, dematerialisation. The non-renewable material required to make one unit of product has been reduced by around 40 wt% in the 7 years from 1997 to 2004. This has reduced the net inputs required and consequentially reduced environmental impacts, as well as providing the benefit of an economic saving of US$ 299 million to the business (Interface Sustainability, 2007).
Broadloom carpet is usually cut from a standard width roll at the point of installation. Carpet tiles are also cut from broadloom when they are manufactured. The tiles are then installed in a broadloom pattern, where the tiles are cut at the edges. It is important that all tiles are manufactured from the same roll of material as there will be slight variation by colour between batches. Just by using carpet tiles, the main product of InterfaceFLOR, in place of broadloom carpet, installation waste can be reduced by 67% (Interface, Why Modular?, 2003). The waste will arise as the carpet tiles are cut at to fit the edges of the room and cannot be used elsewhere.

In 1998 a breakthrough carpet tile was developed at InterfaceFLOR based on the concept of biomimicry- the idea that natural systems can guide the design of man-made products (Benyus, 1997). As previously explained, typically carpet tiles have to be laid in a predefined pattern to achieve the desired visual effect, creating small amounts of edge waste. “Entropy” carpet tile is laid non-directionally with a random design so that edge waste can be used in other areas of installation and therefore provides near-zero waste on installation. This tile quickly became the best-selling carpet tile produced by InterfaceFLOR.

The Entropy range has also lead to a series of introductions also based on biomimicry but incorporating contemporary styles. Using this type of tile can extend the lifestyle of the installation, as tiles can be interchanged when different traffic areas exhibit different wear rates.

InterfaceFLOR, US, has introduced a carpet tile which can be manufactured using post consumer recycled polyvinyl chloride (PVC). ReEntry is the name given to the take-back programme whereby tiles that have been returned to InterfaceFLOR are refurbished and then donated to non-profit organisations or recycled into backing materials (Interface website, 2007).

There has also been the introduction of ‘Cool Carpet’, the industry’s first climate neutral carpet. The level of greenhouse gas associated with the life cycle of the carpet, expressed as CO₂ equivalent, is offset through investment in projects that reduce or reverse the impact of those emissions (Climate Care, 2008).
Since the QUEST (Quality Utilizing Employees Suggestions and Teamwork) initiative has been in place, in conjunction with the EcoSense initiative, there has been a 40 wt% reduction in waste across the board. QUEST is the waste reduction programme initiated in 1995, which allows employees to make suggestions to improve the efficiencies of manufacturing and office procedures to reduce waste. InterfaceFLOR developed the EcoSense Points System to educate associates about sustainability and help them discover things they can do to work to become sustainable. InterfaceFLOR awards EcoSense Points for the successful completion of activities that fall into categories of environmental management systems, quality management systems, sustainability training, sensitivity hook-up, employee safety and education, resource efficient transportation, EcoMetrics, purchasing and Eco-Efficiency.

InterfaceFLOR has recently begun to tackle other new issues in line with the sustainability strategy, such as the process of innovation and creating sustainable partnerships with international groups. These initiatives are described in the next section.

1.3.3.3 Innovation

Previous to this project, attempts at innovation within InterfaceFLOR had been undertaken. However, the ideas created could easily be stifled within the constraints of a company that is well-aware of its core strengths—producing quality carpet tile in a way that is gradually becoming more sustainable.

At the outset of this project, innovation was being attempted within the company, particularly within the Process, Materials and Research (PMR) group. From the mid 1980s, there were 2 main channels for development: technical from within PMR (then known as Technical Development) and product development from the Design and Development (D and D) team.

Ideas for new developments came from a variety of sources such as analysis of competitor's material, raw materials suppliers, machine builders, contact with testing agencies, process troubleshooting, customer requests, market information, perceived gaps in the product range and some internally generated ideas. The range of development projects was quite wide but still almost exclusively carpet related.
During the 1990s, greater contact with Research and Development and Product Development in the US. parent company arose via meetings, exchange of reports and some common research projects. An initiative "Continuous Stream of Innovation" (CSI) was set up under the direction of Ed Terry, the president of Interface Research. The initiative had projects covering a wider range than before and now included backings, antimicrobials, fabrics and anti-soil surfaces. These were however still mainly carpet related.

By 1996, through evolution, Technical Development became PMR which now covered the sites in Northern Ireland, England and Holland. This helped to provide effectively a wider ideas base. D and D likewise acquired more of a European dimension and greater cross-fertilisation of ideas was possible through contact between the UK department and those in Holland and Germany.

Up to the appointment of an Innovations Director developments remained largely carpet and carpet tile related, however a few ideas for recyclability involving modules with detachable top surfaces had arisen. In 2000 a cross functional Process, Design and Product team including individuals from PMR, D&D, Sampling, Engineering and the Print department was set up and provided a number of innovative development leads. However, the priority for development remained variations of that which had been done before and these innovative ideas were not given the resources necessary to continue their development.

A decision was made within the European arm of InterfaceFLOR that the process of development needed to be re-thought and the role of Innovations Director was established. The Innovations Director has responsibility for bringing an Innovations Pipeline of ideas, products and services to completion. The pipeline contains a number of novel concepts for redesigning flooring for InterfaceFLOR. These have been the result of ideas created over the years that had not had the time or the push to develop further.

The previous approach to development had involved pushing products forward towards the goal of sustainability, via the use of the 7 fronts described in section 1.3.3.2. The decision was made that progress should be looked at from the view of the final goal of sustainability, back towards those achievements. Innovative concepts were sought that could be the ideal sustainable floor.
In order to assist in the creation and development of these ideas InterfaceFLOR facilitated a number of Innovations Workshops. The principle aim of these workshops was to formulate new ideas for the floor covering and interiors market based on "the principles of sustainable living and restorative behaviour". The first of the workshops took place on 12th and 13th May 2004, with the participation of a group of experts from a variety of backgrounds designed to give a good mixture of creative ideas and inputs. There were people who describe themselves as sustainable thinkers, textile technicians, marketers, consultants, sustainable designers, academics and engineers.

This exercise showed that external persons could be particularly useful in creating a different view on a problem that had been tackled for so long in a particular way. This group also provided expertise that could not be found within InterfaceFLOR. The workshops were very successful and provided external guidance as well as new ideas and concepts to the pipeline. The participants from the Innovations Workshops then began to collaborate with internal Interface experts and subsequently this group were called the 'Innovations Network'. There was the added advantage for those from InterfaceFLOR within this network that time was dedicated to free-thinking and pure innovation, without distractions that would have previously taken over.

The members of the 'Innovations Network' ultimately became watch keepers of the Innovations Pipeline to ensure that the main purpose of the Innovations Team and the innovations concepts did not become diluted. One such an innovation concept, described as 'Pour Man's Floor' - a fluid biopolymer flooring that is entirely biodegradable is described in chapter 4. Another concept is known as Just\textsuperscript{TM}.

Working with partners in India, InterfaceFLOR is currently developing Just\textsuperscript{TM}. It is a customisable flooring system using locally available natural materials and traditional craft skills. The enterprise aims to improve rural income generation for women artisans and tiles are developed in collaboration with a leading natural fibre exporter based in Bangalore. The tiles are hand made in India using traditional materials and craft skills and potentially may be validated through fair trade style partnerships. The project is a collaboration involving InterfaceFLOR, Experience Design Lab and Industree Crafts Foundation.

A photograph of some of the work produced is shown in figure 1.6.
The result of the workshops and the network is that InterfaceFLOR now has a different perspective on innovation. The group of innovators—both internal and external will validate the concepts. Budgets, plans and classic product development are undertaken for them, but outside of the regular business. Only when the concept is fully formed will it be taken back into the business for internal support in a more traditional way.

InterfaceFLOR has learned through this process that it is not possible to undertake innovation alone. The business needs to support the idea of ‘innovation’ as something which does not have 100% success. Agreement and certainty are not always necessary for these projects as they had been for previous incremental product improvement (Stacey, 1996). Just™ is an example of a project that had a high degree of agreement within the business, but much less certainty for success. Innovation can reside in that part of the agreement-certainty matrix where ‘co-creating’ methods lie. This is shown by figure 1.7 below.
By undertaking more successful innovation within this area, it is more likely that agreement may be obtained from the business on future projects. The projects that may not have been considered before will therefore become more attractive.

The second part of this project is to further the innovative developments that are now taking place at InterfaceFLOR. The aims of the work are described in the next section.

1.4 Summary of Research Aims and Structure of Thesis

There are many ways of fulfilling the needs of a consumer with a flooring product and these are also considered in the description of the categories of flooring, given in Chapter 2. The description of the manufacture of these flooring types is included in this chapter, which show that there are many methods of producing a floor. Some of these manufacturing routes are time, energy or material-intensive. Some of the drawbacks of the flooring are discussed in this chapter such as associated environmental impacts and energy input. This enables a comparison with the aims of InterfaceFLOR and the ‘Mission Zero’.
Flooring requirements are often tested through rigorous quality control procedures and some of these are described in Chapter 2. These tests have been developed with specific flooring categories in order to simulate use in service. The tests often require a finished flooring product and a large volume of material and therefore the drawbacks of the tests are also considered.

The most obvious method of reducing environmental impact, as shown by the LCA data, is to replace virgin material in the current construction with recycled material. This is one way that the flooring material would not be radically altered and performance of the flooring could be maintained. This has been an ongoing part of the development at InterfaceFLOR and continues as evolutionary progression. An investigation that resulted in the introduction of recycled material for InterfaceFLOR is described in Chapter 3, which formed the first phase of this project.

During the course of this project, the impetus at InterfaceFLOR altered and innovative projects were given more precedence. This allowed revolutionary concepts to be considered for further investigation. One such concept is PAF that is described in Chapter 4, which has in turn developed into the second phase of this project. This chapter also discusses the drawbacks of this concept and the implications for InterfaceFLOR. This concept has led to the investigation of a resin based on epoxidised linseed oil (ELO); that is a system based on renewable material and not petrochemicals. This material has potential use in other concepts at InterfaceFLOR and these are described in this chapter.

Chapter 5 describes the investigation of the ELO-based resin that has been identified as a result of the PAF investigation. The material was subjected to different processing conditions and the results assessed. One of the potential uses of this material in the short-term is a flooring product and the further investigation is described in chapter 6. This chapter also includes a description of the flooring tests and Chapter 7 describes the full-scale flooring trials undertaken as part of this investigation.

This report concludes with the recommendations arising from this investigation. These include the use of this material as a flooring material that in high performance flooring testing can be compared to PVC tile.
Chapter 2 Flooring

2.1 Introduction

This chapter goes some way to describe the way in which flooring has evolved over the past several thousand years to give the wide choice of flooring that is now available. This evolution has taken place due to consumer requirements, fashion and has been restricted by availability of materials. In the 20th and 21st Century, due to the increase in international trade, there are now no longer such restrictions on the type of material available. The scarcity of a material is now included in the cost passed on to the consumer.

Flooring can be predominantly divided into two categories- hard (smooth e.g. tiles, vinyl) and soft (textile e.g. carpet) coverings (O’Neill, 2003).

Smooth floorings are further described in section 2.3.2, with a further description of some of the manufacturing methods typical to this category.

Textile floor coverings are described in section 2.3.3. The manufacture of a carpet tile, the main product of InterfaceFLOR is described in this section.

The two categories of floorings will have to provide the same practical functions on a basic level, but the effect on the floorings of foot traffic and wear will be different. For example, a vinyl floor will suffer more visible damage to a scratch from a sharp implement than a carpet. However, the vinyl floor will appear to resist more than carpet the wear endured by repetition of a castor chair movement. If a new flooring product were to be introduced to the market, it would have to pass the current standard testing. The typical quality control procedures for flooring are discussed in section 2.4. This section includes a brief description of the way in which the British Standards are created and implemented.

The British Standards are designed to simulate practical use, in order ensure that flooring fulfils consumer requirements. There are many types of flooring that are specified for the home and a description of the categories of flooring is given in section 2.3.
2.2 History

Flooring has evolved over several thousand years as customer requirements, tastes and fashion have changed. In early homes the floor was just a patch of dry ground that offered some respite and shelter under a dry roof. This is still true in many parts of the world, such as rural Africa, where cost is an important consideration, materials are scarce and the weather is warm and temperate. Dry ground is an inexpensive surface that can easily be levelled and modified to create a floor. Hay, straw and cow dung are sometimes also added to the surface and trampled down to create a surface almost as hard as cement.

Figure 2.1. Interior of Mexican hut (Mexico Woods, 2008)

The above figure shows a simple dirt floor, in a style still commonly seen throughout developing countries.

In early North American homes sand was often placed on the floor, sometimes in decorative patterns and swept out of the room when the litter and debris became excessive. Peanut and sunflower seed shells were added to the floor so that they could be crushed underfoot, producing oil, which retained and settled the dirt (Huntington, 2004).
Other early forms of decorating the floor led to the Indian tradition of rangoli, which is a painting made from rice flour and petals created for a special occasion or to greet visitors. This is one example of how the floor can provide a unique welcome. This idea of a welcome mat has been developed further in recent years more as a functional entity than a decorative piece.

There were technologies developed in order to adapt to the materials locally available as well as practical needs. Decoration has influenced heavily the method of construction of these floors. For example, the Romans used small tiles in their mosaic construction in order to create more intricate patterns.

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Stone floors have been used since the Egyptian times as coloured tiles were used to create mosaic. This can be traced from 5,000 years ago, through to the Roman Empire. The Romans then discovered another more sophisticated benefit of using stone floors- under-floor heating. A fire would provide heat through the space underneath the tile floor. Tiles came in and out of fashion over the next few thousand years and under-floor heating has remained a preserve of the well off (Huntington, 2004).

During the Middle Ages in Europe floors were often made of trampled down debris as people sometimes shared their living space with their animals- although generally in different rooms. Although the floor was made from waste, a primitive attempt was made to improve the interior by adding mint to the refuse. Crushing the mint underfoot would create deodorising smells, akin to a modern day air freshener. This is yet another example where flooring does not simply provide functionality but offers added value to the room.
Wooden planks were first used as floors in the Middle Ages, before being sanded, sealed with varnish and decorated in later years. Stains were used to imprint decorative patterns on the floor. This is yet another example of a simple, natural floor, made from a construction material widely available.

The oldest known rug discovered was from around 400 BC (the Pazyryk carpet), although there is evidence that carpet-weaving dates back to around 4,000 years ago in Egypt, Mesopotamia and the Middle East (Art Arena, 2007). The carpet industry has continued to grow and diversify through the industrial revolution and the movement to tufted carpets from woven, the manufacture of which is described in the next chapter.

Other types of resilient flooring such as rubber, cork, asphalt, vinyl and linoleum have been in use since the late 1800s and these are now second only to carpet in terms of sales. Some of the processing routes for these types of flooring are described in detail in the next chapter.

The history of flooring has shown that not every development made in flooring has an associated practical benefit. This may lead to the conclusion that there is more value from a floor than simply function and the social attributes were discussed in the previous chapter. The next section describes the way in which flooring is now categorised.

2.3 Categories of Flooring

2.3.1 Standard Descriptions

As previously mentioned, flooring is distinctly divided into two categories; hard (smooth) and soft (textile) coverings. These categories have been designed to provide a distinction between typically textile floors like carpet and those harder floorings such as ceramic tiles and vinyl.

Textile or soft floor coverings are those that have been traditionally used in the UK, whilst smooth floors have been more predominate in hotter climates such as Southern Europe. Smooth flooring also has traditionally formed the base of the floor in colder climates, such as Scandinavia, where they are often accessorised with textile coverings.

Smooth floor coverings are a disparate group of materials that encompass everything that is not considered to be textile. This group includes vinyl, laminates, wood, linoleum, cork and stone.
Vinyl is a sheet, manufactured from PVC and filler, which is offered both with and without a cushioned underlay and as vinyl tile. Laminate floor coverings are manufactured from resin-impregnated paper that is sandwiched together by either direct or high-pressure methods. Wood and cork floor coverings can be processed and manufactured from trees. Linoleum is similar to vinyl in appearance although it is formed from linseed oil and filler like cork. Stone is often quarried, ground, cleaved and polished to manufacture tiles.

Textile floor coverings are mostly fitted carpets (Mintel, 2006), although rugs can be included under this description. This group includes woven carpets, tufted carpets, fibre-bonded carpets and carpet tiles. These are discussed in more detail in section 2.3.3.

Woven carpets were traditionally produced from wool although man-made fibres are now more commonly used (Carpet and Rug Institute, 2003). Tufted carpets are manufactured by stitching yarn into jute or a synthetic backing such as polypropylene, which is then kept in place by use of an adhesive. Although tufted carpet was originally available only in nylon, polypropylene is now the more commonly used (ibid.). As with woven carpet, the use of mixed fibres is common. Fibre-bonded carpets are made by needling or entangling a blend of fibres to form a web that is treated by heat or resin impregnation. The manufacture of carpet top cloth, the top surface of a carpet is discussed in section 2.3.3.2.

Carpet tiles may be fibre-bonded, fusion-bonded or tufted. They are manufactured in a similar manner to carpets, but then given a secondary backing and cut to size. Non-fixed floor coverings are smaller textile-based elements such as rugs, but this category excludes doormats, bath and toilet pedestal mats.

The standard categories of floor coverings are useful in describing the types of flooring and understanding their subsequent successes. Each flooring type offers different qualities that satisfy the needs of consumers that were discussed in the previous chapter. It is also useful to consider the specific attributes that they provide and typical manufacturing methods that are described below.

### 2.3.2 Smooth Flooring

#### 2.3.2.1 Introduction

The UK smooth flooring market has increased in value from £511 million in 2001 to £689 million in 2005 (Mintel, 2006). Smooth flooring has become much more accessible in recent years as it has become easier to install, in particular with the arrival of laminates.
Laminate now makes up 65% by volume of the smooth flooring market, although vinyl has been making a comeback with an increase in the last three years to 27% sales by volume in the UK (Mintel. 2006). The remainder of the smooth flooring market is mostly taken up by ceramic tiles and linoleum. For nearly a century between the 1870s and 1960s, linoleum was the most widespread manufactured floor covering in existence (Sarin, 2005). It was mostly superseded by the vinyl industry, although it still retains a small market presence. The data for sales by volume in the UK is shown in figure 2.3 and figure 2.4 below.

**Figure 2.3. Floor covering sales by volume in 2003 in the UK (Mintel, 2006)**

**Figure 2.4. Floor covering sales by volume in 2006 in the UK (Mintel, 2006)**
The smooth flooring industry is worth around 35% by value of the flooring industry, whilst it is actually only 23% by volume. This is because smooth flooring is sold at a higher average price of £13.85 per square metre, compared to textile flooring that is sold at an average of £7.56 per square metre (Mintel, 2006). Much of the recent price increases could be attributed to the trend away from cheaper laminates to more traditional and expensive real wood flooring.

An appreciation of other flooring industries and their evolution will aid a comparison with the current state of the carpet industry. If InterfaceFLOR are to introduce an entirely new flooring concept, the manufacture of other flooring products should first be understood. This knowledge may facilitate the understanding of both the place in the market and the route to market for a revolutionary concept. The manufacture of laminate, the largest sector in the smooth flooring industry is described in the next section.

2.3.2.2 Laminate

Plastic laminate is processed by combining two different layers of paper or thin wood, a decorative layer and a clear surface layer. The colour, patterns and textures that are visible to the consumer are the decorative layer and the clear surface layer is the material that protects the decorative layer from abrasion and moisture. After selection of the decorative layer, which may typically be decided by the type of wood to be imitated, the two layers are laminated together under high pressure. Decorative laminates vary in thickness, depending on the number of slices of paper, generally the thicker the paper, the greater the durability.

In general, laminates are inexpensive compared to many materials; it is typically a third of the cost of hardwood flooring (Terra Fina, 2007). They are available in many styles, while maintaining a low budget cost. It is a durable material, but can be cut by knives or other sharp objects. Plastic laminate has proven to be stylish, durable, economical and beneficial (Tan and Murray, 2003).

Since laminate is made from a potentially sustainable source (wood) it could potentially form part of the portfolio of material which would lead InterfaceFLOR towards the ‘Mission Zero’. However, the laminating process has potentially high impacts since large amounts of heat, pressure and adhesives are required (Formica, 2007) and these other challenges are still to be addressed fully.

Outside of the laminate industry, manufacturers of vinyl and floor tiles are moving away from cheap products and trying to drive prices higher by injecting innovation and flair into their offerings (Mintel, 2006). One such product, produced by InterfaceFLOR is called Interlock, a 100% PVC tile, described in the next section.
2.3.2.3 Interlock

Interlock is a smooth flooring product manufactured by InterfaceFLOR. The specifications for Interlock are that it is a resilient flooring tile that is manufactured from 100 % recycled post-industrial waste. It is available with four different top surface patterns in 10 colours and is available with an anti-static finish. It is a hardwearing, anti-slip, practical and durable flooring that is suitable for light to heavy use such as can be found in an industrial setting.

It is also flexible enough to be used for exhibition stands, retail and hospitality as the installation can be fully bonded to the floor by glues, tackified so that it can be removed more easily than glue, or laid loose (Futureproof/ed, 2007). Once it has completed its useful life, the Interlock can be itself recycled back into Interlock since it is a 100 % PVC product.

An example of an installed section of Interlock tiles is shown below.

![Interlock installation](image)

*Figure 2.5. Interlock installation*

Interlock is produced using an extrusion process, relying on a heating and cooling cycle for the PVC to form the shape required. This is achieved using a heated extruder and mould.
The specifications state that Interlock should be manufactured from post-industrial waste, thereby reducing environmental impacts over the life cycle of the product. There has been a lack of consistency with the quality and quantity of feedstock and therefore virgin material has had to be used for most production. There are a number of concerns regarding the manufacture of PVC that are still being addressed such as the use of plasticizers, chlorine use, dioxin and furan production (Carrol Jr et al, 2000). The chemicals produced as by-products in the production of PVC have also been linked to increased likelihood of certain cancers, including testicular (Ohlson, 2000).

Chemical recycling of PVC is environmentally less preferable and less attractive in economic terms than mechanical recycling, such as that used in the InterfaceFLOR ReEntry programme. There are therefore a limited number of initiatives that have resulted in the construction of industrial plants, or may lead to the creation of such plants in the near future (European Commission, 2000). In the year 2004 within the European Community (EC) around 3 wt% of post-consumer PVC was recycled compared to 82 wt% that was sent to landfill and 15 wt% that was incinerated (European Commission, 2004).

Incineration is a method of disposal that is worthy of note in the example of vinyl, with careful consideration for emissions. Approximately 600,000 tonnes of PVC are incinerated per year in the EC. PVC represents about 10 wt% of the plastic fraction incinerated, although it contributes between 38 and 66 % of the chlorine content in waste streams being incinerated (European Commission, 2000). On incineration, PVC waste generates hydrochloric acid (HCl) in the flue gas that requires deactivation with a neutraliser such as lime. It is estimated that the incineration of PVC results in, on average, 1- 1.4 kg of residues with this lime process per kg of PVC incinerated (ibid.).

PVC is also currently the largest contributor of chlorine into incinerators, which contribute around 40 % of the dioxins into the EC. Dioxins have been linked to a number of health concerns. It has been suggested that reducing the chlorine content in incinerators will reduce the production of dioxins (European Commission, 2004).

It therefore seems obvious that InterfaceFLOR cannot include the use of PVC when aspiring to the ‘Mission Zero’ of no impact on the environment. A single polymer product could be one way to ‘close-the-loop’ so that one product can be entirely recycled into a new product. This could not occur indefinitely since there is invariably foreign material that is introduced at the recycling stage. This is worthy of thought when considering new flooring concepts.
Another product, manufactured from PVC, that has dominated the market until recently is vinyl, described in the next section.

2.3.2.4 Vinyl

Vinyl flooring can be manufactured in a number of ways. It was originally created as a more resilient version of linoleum, the manufacture of which is described in the next section.

The vinyl structure is a composite of a number of layers of material (shown in figure 2.6). The top surface is a thin polyurethane coating which is designed to be easy to clean as well as resistant to scratches. It lies on top of a PVC layer, designed to provide the wear resistance since it provides the bulk of the structure just beneath the surface. A layer of fibre glass underneath the PVC provides dimensional stability and a final layer of PVC compounded with filler and plasticizers gives weight and further stability.

![Figure 2.6. Structure of typical vinyl flooring product (Forbo, 2007)](image)

The layers are brought together separately on large rolls and the PVC mix is heated to set the mix in place. This results in large rolls of material that are then cut for installation. Vinyl tiles can be cut to squares from the large rolls and installed as separate pieces.
The vinyl industry has attempted to address the environmental challenges by reducing the energy required to manufacture, the water usage and the waste created during the manufacturing process (The Vinyl Institute, 2007). However, there remains a large amount of embodied energy in the finished product and it has been shown that it is difficult to reuse, recycle or dispose of without environmental damage. This would make it unsuitable for InterfaceFLOR to consider as part of a portfolio of products when it becomes a sustainable company. The resilience of vinyl can lead to long service life in comparison to other materials such as carpet and can make it an attractive product.

Vinyl was designed to provide greater resilience than linoleum flooring upon which it is based. The history of linoleum and the manufacturing method are described below.

2.3.2.5 Linoleum

In 1860 Frederick Walton, a rubber manufacturer in England, during his daily work noticed that linseed oil formed a leathery skin on top of paint. He realised that he could put this characteristic of the oil to good use as a rubber substitute when reduced, mixed with filler and pigments and dried on a canvas backing (Simpson, 1999).

He later improved this invention and in 1863 applied for an extended patent on what he called ‘linoleum’, manufactured from the mixing of linseed oil, powdered wood or cork, resins, pigments, ground limestone and drying agents. Frederick derived the term linoleum from the Latin words for the flax plant and oil: *linum* and *oleum* respectively (Sarin, 2005).

The floorcloth or oil-cloth industry was widespread in Scotland and Lancashire during the mid-nineteenth century. It had begun in the early eighteenth century as a large-scale industry and the process had changed little since. Canvas was tightly stretched across wooden frames in large rooms and workers would use wooden platforms to support themselves as they applied the constituents with trowels and large brushes. They would paint the cloth with size, a thin liquid designed to seal the canvas, much like a primer, followed by the addition of thick paint. Pumice stones were used to create the smooth finish desired. The floorcloths would then be moved to a printing room for the application of patterns before a final varnish to seal the design (Manson, 2003).
The advantage of the new linoleum was that it was thicker, more resilient and waterproof. The industry began to expand rapidly as the demand for such a floor covering increased and floorcloth manufacturers began to imitate the manufacturing techniques and constituents. It had taken less than three years between the patenting of linoleum and the report of steady sales from the Linoleum Manufacturing Company and three years later it was exporting to the USA and Canada. This shows that a flooring material that fits a specific need can be hugely popular within a small amount of time.

Between 1874 and 1913 the volume of linoleum exported from the UK increased tenfold, despite the overall reduction in exports of 29 % (Sarin, 2005). The production of linoleum continued to diversify with more economical and resilient products becoming available and the use of material from international sources-linseed oil from America, cork from Portugal and Spain, jute from India and Pakistan and limestone from the UK.

For nearly a century from the 1870s to the 1960s linoleum was the most widespread manufactured floor covering (ibid.), until it was usurped by the vinyl industry. The process of manufacturing true linoleum is time-consuming and has changed little in process since Frederick Walton’s last patent application.

Linseed oil is derived from the flax plant. It is an annually self-pollinating plant that takes around 100 days to mature to between 40 and 91 cm in size (Flax Council, 2005). The raw oil is extracted from the seeds via hydraulic pressure and is pale in colour (Encyclopedia, 2005).

Linseed oil was originally oxidised through the process of boiling in a lead vat to form a viscous substance called linoleum cement (Flax Council, 2005). However, oxidised linseed oil is now produced via the addition of chemical accelerators to heated raw linseed oil to decrease drying time. Oxidation of the linseed oil results in a relatively stable compound.

The linoleum cement is then mixed with pine resin, rosin, cork, woodflour, chalk, clay and pigments to form sheets on a jute or hardened canvas backing, which could all be renewable material. Figure 2.7 shows the ingredients used in linoleum.
Figure 2.7. Components used in linoleum manufacture (Sanz, 2006)

This is then heated to 70 - 90°C in seasoning rooms, which accelerates the oxidation and consequently toughens the linoleum. The photograph in figure 2.8 shows a roll of linoleum.

Figure 2.8. Inspection of a finished linoleum role at Kirkcaldy, Scotland (Image Bank, 2007)
The linoleum is then seasoned for two to four weeks at this elevated temperature in the drying rooms.

Since the colouring of linoleum now goes through the entire surface, the design can continue to be seen as the product wears away. Scratches can be disguised or erased by abrading the surface to a smooth finish. Linoleum does not burn readily, or absorb liquids, making it extremely suitable for areas such as kitchens. It can therefore be mopped and scrubbed using conventional detergents even in high traffic areas. It does not generate static electricity (Green Floors, 2005). Indoor air quality is becoming of increasing importance to consumers and this is less affected through the introduction of linoleum than vinyl (Advanced Buildings, 2005). During use, linoleum does not require the addition of anti-bacterial agents, as this feature is inherent in the product. It is naturally antimicrobial and inhibits the growth and spread of microbes (iFloor, 2006).

At the end-of-life the material will ultimately biodegrade and does not give off any hazardous emissions during decomposition. Incineration is also a viable option for disposal as linoleum has a similar calorific value to coal (18.6 MJ/kg) and the amount of CO$_2$ given off during this process is similar to that taken up during growth of the natural raw materials (Green Floors, 2005).

Linoleum is obviously an attractive material from an environmental point of view due to the low embodied energy and high use of renewable material. The linseed oil is particularly attractive as a raw material as it may be processed in different ways. This is again worthy of note when considering future flooring concepts. Linseed oil will be revisited in Chapter 4. Linoleum as a flooring product has proved less popular in recent years as there have been other innovations in the smooth flooring industry. Textile floor coverings remain the biggest segment of the flooring industry. They are described further in the next section.

2.3.3 Textile Floor Coverings

2.3.3.1 Introduction

Textile, or soft floor coverings remain the flooring of choice in the UK. 178 million square metres of soft floor covering material were estimated to be sold in 2006. Although this was less than previous years it remained at 77 % of the market. By value the market share of soft floor coverings is lower at 65 %, and is valued at £1,360 million (Mintel, 2006).
Tufted carpet dominates the soft flooring industry with a 79% by volume market share, which represents sales of over 140 million square metres. The remainder is shared between woven (9%) and needlepunch and others (12%). Needlepunch and others are the cheapest type of carpet and have suffered from a consistent decline in value. This is largely because those consumers who are purchasing carpet are opting for higher-quality types.

Carpet tiles are manufactured using the same methods as soft flooring, since it is itself categorised as soft flooring. The manufacture of a carpet tile is described in the next section.

2.3.3.2 Carpet Tile Manufacturing

2.3.3.2.1 Introduction

A carpet is essentially composed of face yarn, primary backing, a bonding compound and often a secondary backing. The majority of carpet is manufactured by tufting—using mostly nylon yarns. This process is described in the next section.

Wool was the traditional material used in carpet manufacturing and is made from renewable resources. In the 1960s viscose became more fashionable and was tried as a cheaper alternative. However, its wear properties were poor, it flattened and burnt easily in comparison to wool (Colton, 2004). Nylon was then added to wool at 20% by volume. This increased the durability considerably, whilst retaining a similar feel (Carpet and Rug Institute, 2003). For example, wool carpet typically survives 7-9,000 revolutions of an abrasion machine, whereas a 20% nylon addition increases the survival to 30-50,000 revolutions, as defined in British Standard EN 1813:1998.

The parallel expansions in the plastics, petrochemical and oil industries resulted in a reduction in cost and a consequential boom in the plastics industry (Subramanian, 2000). Hence the use of nylon began to increase considerably at the expense of natural materials. By 2003 the use of wool had declined to its lowest point ever in the history of the carpet industry (ibid.).

Carpet tiles are manufactured in the same way as broadloom carpet initially and then backed with a series of materials to provide stability. Much of the wear on a carpeted floor is concentrated in small areas such as doorways, under desks and around furniture—typically around 20% of the surface. The use of modular flooring means that this section can be selectively replaced—offering savings on cost and material (Interface, Why Modular, 2003).
Modular installations are also much faster to install than conventional carpet, typically saving 50% on man-hours. This is because there is no underlay required, no seaming or dye lot mismatches. If a specific design is required, with modular tiles there is the flexibility to add larger patterns and expand aesthetic possibilities. It offers the customer some creative freedom and design flexibility. The design of the floor arises from the face cloth that is manufactured before backing. This is described in the next section.

2.3.3.2.2 Face Cloth Manufacture

There are many methods of manufacturing a face cloth of carpet and carpet tile. Some of the most common methods are described in this section.

Tufted carpet styles range from loop and cut pile to combinations of cut and loop. A tufted carpet is illustrated in figure 2.9. They often offer different pile heights across the carpet that results in different patterns within the carpet, as different colour threads can be made prominent. Stepping or zigzagging using individual needle bars is used to achieve this. Higher priced wool/nylon blends are also produced by this method, although the nylon yarns, in particular the continuous filament nylon, predominate the tufted market.

Figure 2.9. Illustration of tufted carpet (Dryfusion, 2008)

The patterning capability of tufting mechanisms is somewhat limited, although newer developments of computer controlled independent controlled needles (ICN) and servo adjustment of pile height have widened the scope of possible patterning. Traditional woven carpet is produced in smaller quantities and offers a greater amount of variety. Axminster and Wilton are some of the better known woven carpets produced in the UK. The principle of the carpet making is that the pile yarns and the backing yarns are interlocked and this method has changed little in the last 200 years.
In an Axminster carpet weave cut tufts of yarn are inserted at the point of weaving by means of grippers. The appropriate coloured ends of the yarns are selected by jacquard mechanisms and presented to the grippers before the tufts are cut from the yarn. This means that during the manufacturing process a larger variety of colours can be utilised, although at the expense of greater energy considerations. This is shown schematically in figure 2.10.

![Figure 2.10. Schematic of Axminster carpet construction](image)

Woven carpet will absorb considerable dynamic loading in use since it is not possible for the backing to delaminate, as it is an integral part of the carpet. The whole carpet is three-dimensional and up to twelve backing yarns supports each individual tuft. The history and manufacture of this type of carpet consequently means that it has gained a reputation for resilience and luxury.

Needle punched or needle felt carpet has developed as a result of the need for more versatile materials and cost reduction. One or more fibre webs are laid lengthwise, crosswise or diagonally and are processed through the needling machine. Different colours of web may be combined to give a decorative effect. The needling process punches the fibres through the web, causing entanglement and consolidation of the web structure. In this manner, a dense, wear resistant felt structure is produced. Further needling processes can be used to create a raised pole structure in a predetermined pattern. The resulting material is then anchored using a latex binder, compressed and levelled on a press or calendar. This is shown below.
Figure 2.11. Schematic of needlefelt carpet

Fusion bonded carpet is produced by implanting loops or yarns directly onto an adhesive coated backing. The yarns are not stitched into the primary backing before the adhesive is applied and may be cut before or after application.

Fusion bonded products are often printed after construction for specific patterns. The pattern is sprayed on, rather like the method employed by an ink-jet printer so the designs are very detailed and can be very exact. The print is set using steam and then cooled and washed off to complete the design. This pattern will tend to be less durable than those created by pre-dyed yarn since the colour does not penetrate throughout each individual tuft.

This section has shown that the manufacture of the face yarn is energy-intensive, no matter what method of construction is used. InterfaceFLOR has ensured that there is 100% renewable energy powering the UK sites and so this concern could be discounted. However, energy use, no matter what the source always remains a concern. The resulting embodied energy in the carpet is high and it would be prudent to reduce this to fit in with the sustainability objective.

2.3.3.2.1 Application to the Backing System

There are a number of systems available for backing carpet before cutting into carpet tiles. Two main methods of backing the carpet tile at InterfaceFLOR are used. They are known as Graphlex and Glasbac, illustrated in figure 2.12 and figure 2.13. The application of the backing systems results in tiles that are versatile enough to be fitted quickly with minimal floor surface preparation.
The Graphlex backing is a patented system that is a bitumen composite modified with polymer and filler, incorporating layers of fibreglass fleece and a single layer of polymer fleece. The fibreglass is multidirectional and consequently confers dimensional stability. It is desirable that the backing system be relatively dense so that it will resist warping, wrinkling or doming under heavy traffic or extreme changes in humidity and temperature.

The Graphlex backing is a backing contains, by weight, 3 % fibreglass, 1-2 % fleece and over 95 % bitumen mix (33 % pre-modified bitumen, 67 % limestone). The bitumen is applied hot and cooled to allow it to set. The Graphlex processing line is described in more detail as part of the processing analysis in Chapter 3.

![Figure 2.12. Illustration of Graphlex backing system (Interface, Backing Systems, 2003)](image)

The Glasbac system is a thermoplastic composite that again incorporates fibreglass for dimensional stability. In place of bitumen as the primary backing material, PVC is used.
PVC is relatively expensive in comparison to bitumen and is therefore filled with more cost effective materials. It is mixed with plasticizers, resins and fillers in order to bulk the mix. The plasticizers and resins allow more filler to be added. In the case of InterfaceFLOR, the filler used is graded virgin limestone.

The tufted top cloth will normally have already been pre-coated with an adhesive system before it is processed with the Glasbac system. This pre-coating takes place at the same manufacturing site. Different compounds are applied, depending on the yarn system used. The top cloth is presented in a continuous roll via the use of a sewing system. The end of the roll being processed is attached to the beginning of the next using an adhesive strip. It is heated to around 160 °C (± 5 °C).

The top cloth is wound into bins to store the excess which ensures that the remainder of the processes can take place continuously. The tension on the pre-coated system can be altered to allow for different systems of face yarn.

The pre-coated tufted cloth is then presented at PVC Station 1 (figure 2.14). At this point, room temperature PVC mix is applied to the back of the cloth. It is delivered via 1.5 tonne batches from the PVC compounding site. At the PVC compounding facility the PVC is mixed with fillers, additives and plasticizer. The amount and type will depend on the customer requirements.
Figure 2.14. PVC being applied to the top cloth

A levelled blade controls the amount of PVC mix applied. This can be raised or lowered depending on the thickness of the top cloth and the amount of PVC mix required. The flow-rate of PVC mix depends on the opening of the taps, which are operated by hand.

At PVC Station 2 a sheet of fibreglass is coated with PVC mix in the same manner at room temperature, although here it is thicker to avoid the PVC mix striking through to the top cloth. The two sheets are then sandwiched together, with the PVC mix in between, as shown in figure 2.15.

Figure 2.15. Schematic of PVC application
The drum is heated to 150 °C (± 10 °C) for most applications of PVC. This aids the cure of the PVC before another layer of fibreglass and PVC is added. The sandwich is then taken to Station 3 where a further layer of PVC is applied. Again here the thickness of PVC that is applied can be altered through the use of a levelled blade. The entire system is then sent to an oven to accelerate cure.

The oven is typically held at 160 - 180 °C, although it can be lowered to room temperature if required when there is a stoppage in the line. A camera is used to measure the surface temperature of the carpet, and the information is used to control the output of an infrared heater.

On removal from the oven an embossing roller applies a pattern to the PVC. This pattern is set as the system is then cooled on two cooling drums. These are kept cool through the use of chilled water. This is shown in figure 2.16.

![Figure 2.16. Embossing of pattern onto PVC paste](image)

Once the system is cool, details of the particular carpet tile and other order specifications are printed over the embossing on the back of the tiles. The tiles are then cut out of the large roll using a press.

The line speed can be altered depending on requirements, up to 10 m/min in 0.1 m/min increments. It is typically held at around 5 m/min.

This analysis of the Glasbac system shows that again there are a large amount of energy inputs required to create the finished tile. It is also obvious that the material used as a backing, i.e. PVC, could be replaced with some other material relatively easily. This could be a material based on renewable resources for example. This would not entirely fit with the sustainability objective but would be an evolutionary step towards it.
The finished carpet tile will then undergo a rigorous series of testing and quality control procedures to ensure that the quality of the product remains consistent. These are described in section 2.4.

2.4 Quality Control

2.4.1 Introduction

Flooring will undergo testing as part of quality control procedures. This is to ensure that a consistent product is delivered to the customer that fits a pre-defined standard. The same tests are applied to new products within each flooring category. Therefore if a flooring product were introduced with a novel material or novel structure it would have to satisfy the current flooring tests.

Flooring is tested using a variety of methods that are intended to mimic the use expected in practice. These tests are designed to ensure that the customer receives a product that satisfies their practical needs. It may be that new tests are required to assess a flooring solution that does not follow the traditional method of construction, but offers different attributes. The process of implementing new tests is long and complex (Nunney, 2004). There have been new wear tests for flooring suggested in the literature (Kuisma et al, 2004) but since these have not yet been implemented as British Standards they are not considered here and only standard testing procedures are used. The current testing procedures that are described here will be used to assess any novel flooring product.

Carpets, irrespective of type, undergo a series of tests in order to assess their contract level—the number given to a carpet to define its capability in use. Natural materials are difficult to test under these criteria as by their nature they vary between batches and consistent properties are often not achieved.

The British Textile Technology Group (BTTG) is historically the independent testing house that is responsible for validating test procedures. It was this house that developed the current carpet testing based on woollen carpets.

BTTG was formed in 1988 following the merger of the Shirley Institute and the Wool Industries Research Organisation (WIRA), which had been involved in testing materials since 1919. It has a number of subsidiaries including BTTG Ltd (established 2003), Fire Technical Service (FTS), British Carpet Technical Centre (BCTC) and Advanced Materials Services Ltd (Nunney, 2004).
It is an independent organisation, funded by a variety of methods including commercial testing. BTTG prides itself on its stringent objectivity and even offers an expert witness service. BTTG also participates in EU funded work, contributing to the development of European standards and acting as the official UK testing body for European ecolabelling and product certification schemes.

The tests offered at BTTG are varied and encompass all floor coverings. The tests are further divided by category of flooring. WIRA, which became part of BTTG, developed the current carpet testing procedures based on woollen carpets. These tests focus on abrasion resistance, dynamic loading, static loading, flammability and appearance retention.

British Standard BS EN 1307:1997 describes the general classification and testing of carpets. Each test is designed to simulate what may happen to the carpet in use. For example there is included colourfastness- to light, rubbing wet and dry, fibre integrity and fibre bind for synthetic carpets. Each test results in a classification that may be given to the carpet to indicate its quality. The tests that are conducted as part of quality assurance procedures at InterfaceFLOR are described below.

2.4.2 Testing Procedures

This section describes many of the testing procedures that are undertaken on a regular basis at InterfaceFLOR, which follow the British Standards. BTTG and other independent test houses will also undertake testing for InterfaceFLOR that is not available on-site, such as some flammability tests. They are all used to determine both production quality and to determine the grading to be given to new products.

The castor chair test is described in BS EN 985:1995 and is designed to simulate conditions in use. The carpet is simply mounted on a rotating circular test platform of 800 mm diameter. Castors are set on an assembly arranged at 120° intervals and are free to rotate around the 130 mm diameter. The castors rotate at 50 min⁻¹ and the platform at 19 min⁻¹. There will be a suction device to remove any resultant debris.
Figure 2.17. Castor chair test taken from British Standard EN 905:1994

Figure 2.18. Photograph of castor chair test
The whole assembly revolves for a set amount of revolutions, depending on the test, and then the appearance of the carpet is assessed.

British Standard BS ISO 10361:2000 describes the Vetterman drum and hexapod tumbler tests. They both work on the same principle of simulating the conditions of use. The Vetterman drum is a larger apparatus that revolves with a steel ball inside with rubber feet that fatigues the carpet, which is lining the inside of the drum. A circular brush constantly removes broken fibres.

Figure 2.19. Photograph of obvious results after castor chair test

Figure 2.20. Vetterman drum test (British Standard ISO 10361:2000)
Figure 2.21. Steel ball used in Vetterman drum test as shown in British Standard ISO 10361:2000

Figure 2.22. Photograph showing Vetterman drum test on-site

A set amount of revolutions occurs (22,000 for heavy wear, 5,000 for early changes in appearance) and the carpet is removed and examined.
A similar method is used for the hexapod test, but with different dimensions. The carpet is also vacuumed during and after the test to remove excess fibres. A total of 14,000 revolutions are used to simulate heavy-wear and 6,000 revolutions to simulate early changes in appearance or use in less demanding applications.

![Hexapod as shown in British Standard ISO 10361:2000](image)

**Figure 2.23. Hexapod as shown in British Standard ISO 10361:2000**

![Hexapod tumbler cross-section as described in British Standard ISO 10361:2000](image)

**Figure 2.24. Hexapod tumbler cross-section as described in British Standard ISO 10361:2000**
The Lisson Tretrad test, described by BS EN 1963:1998 also describes a method of abrasion resistance measurement (see figure 2.24). A series of rubber feet are loaded and slipped on the sample, similar to the ‘scuffing’ motion that may be expected during typical footfall.
Static loading is tested using BS 4939:1987, ISO 3416-1986, where the thickness reduction in carpet pile is measured after application of a known mass for 24 hours and during recovery after removal of the mass.

Flammability is measured using the hot metal nut method that follows BS 4790:1987. Other European standards have been introduced for flammability as carpet is officially classified as a construction material (Nunney, 2004). The squareness, size and straightness of carpet tiles are measured using a British standard- BS 5921:1980.

Appearance retention assessment follows a set of guidelines set out in BS EN 1471:1997. The carpet is graded visually by trained assessors. They score the change in appearance on a scale. The result is generally a grade for the carpet from 1 to 5. Where 5 is suitable for heavy contract use, 4 is suitable for medium contract use, 3 is suitable for light contract use and 1-2 are domestic ratings reserved for the home market.

Each flooring material can be tested in a similar way and assessed in order to receive a grade. Most floors also undergo in-situ testing within the environment in which it would be expected to perform. This can be the best indicator of performance in service. The drawback with these types of tests is that a finished product is required for testing purposes. It may be prudent to have an intermediate test regime for flooring materials, which could form part of a screening programme with less material.

This chapter has described the many varieties of flooring that have evolved over time and the way that they are now categorised. Any new flooring product would not necessarily have to fit in with these categories. However, it can be seen that the categories are divided so that they fit with the needs of the consumer set out in Chapter 1.

The description of the manufacture of a carpet tile may give some indicator as to how the environmental impact of the current product may be reduced. This could potentially be through the use of renewable material or energy reduction. This will be discussed further in the next chapter.

If a novel flooring product is to be introduced it will have to ultimately satisfy the standard industry tests that have been set out here. This will be revisited in Chapter 6.
Chapter 3 Introduction of Recycled Feedstock

3.1 Introduction

InterfaceFLOR, the host company for this EngD programme, was described in section 1.3.3. The history of the company was summarised as well as the way in which they had come to the ‘Mission Zero’ to become fully sustainable. This section provided an overview of sustainability progress at InterfaceFLOR including the introduction of renewable energy, reducing the quantities of material required and reduction of waste produced in the manufacture of each unit of product. The product has remained essentially the same; a carpet tile, manufactured from non-renewable resources such as nylon, polypropylene, limestone, bitumen and PVC. This was detailed in section 2.3.3.2, which summarised the manufacturing route of the carpet tile.

In order to meet its sustainability objectives InterfaceFLOR requires innovative flooring solutions that are made from renewable resources, manufactured using 100% renewable energy, making no waste in production, recycled and recycleable—either through natural means such as biodegradability and/or through technical means such as product deconstruction. Renewable feedstocks such as poly-lactic acid, wool, hemp and paper have been considered as alternatives for the part of the product that has been identified as having the largest embodied energy—the face yarn (Interface, LCA, 2002). However, none of these have been as resilient, versatile and ultimately successful as the nylon yarn currently in use (Colton, 2004).

The largest contribution by mass to the Graphlex carpet tile is the backing system at approximately 80 wt%, which consists of the bitumen mix, fibreglass and polypropylene backing. The bitumen mix consists of pre-modified bitumen and filler. The filler takes up 67% of this backing system by mass and is therefore a good candidate for substitution.

The standard virgin filler has come historically from natural non-renewable feedstock. Limestone rock is quarried, ground and sieved before being transported to the InterfaceFLOR manufacturing site. The objective set for this phase of the EngD project was to provide solutions to the current manufacturing concerns in order that an alternative supply could be considered. This part of the project was designed to move current product incrementally towards ‘Mission Zero’. The current processing must first be understood before this is considered.
At the establishment of this investigation the limiting factor for line speed was the tile cutter at the end of the manufacturing process. The tiles would be cut from large rolls of product and there would be frequent stoppages at this point. However, this was due to change with the introduction of a new tile cutter and the limiting factor for line speed would consequently change. Hence as part of phase 1 of this project the initial purpose of this investigation was to analyse the process of adding the filler, with a view to optimising the process condition/process parameters, to make recommendations for future use and so to ensure the equipment would perform as designed when required.

The second part of the investigation was to analyse a possible replacement for the virgin filler. The source of the filler is described as well as some of the material characteristics, such as particle shape and size distribution, that were considered important for this investigation.

This chapter is divided into two parts; section 3.2 first describes manufacturing issues associated with the current filler and an investigation which aimed to resolve these issues, section 3.3 describes the recycled feedstock that is considered as a replacement material.

3.2 Review of Processing of Standard Product

3.2.1 Overview

The patented Graphlex backing system is constructed using a double layer of glass fibre reinforcement with a non-woven polypropylene backing and bitumen mix to seal the system together. Figure 3.1 below shows a schematic of the carpet tile.
Figure 3.1. Schematic diagram of Graphlex carpet tile showing layered construction of backing system

In the construction of the Graphlex tile the backing system is assembled before the carpet top cloth is applied. A fibreglass and polypropylene layer are brought together with a layer of bitumen mix applied at the rollers. Subsequently, a further layer of fibreglass is added and second layer of bitumen mix is laid on top in the same manner as before, through an additional set of rollers. This is shown schematically in figure 3.2.
Process controls at this point ensure that the correct amount of bitumen mix is applied at the appropriate temperature and viscosity in order to maintain a cohesive backing system. It is important that the bitumen mix is consistent in its properties and that process controls are in place such that the process parameters can be altered readily. Safeguards are also in place to reduce the occurrence of faults at this critical point of manufacture such as regular inspection and equipment maintenance.
Once the backing system is completed, the tufted cloth is placed on top (see figure 3.3 above). The assembly is then cooled and subsequently solidified using refrigeration. The assembly is then cut to 50 cm x 50 cm squares, resulting in some ‘window waste’ that was previously discarded. However, InterfaceFLOR has recently circumvented this by investing in a recycling system. This waste is ground into small particles and added to the backing system as filler.

Since the fibreglass, polypropylene and face yarn are sourced external to Shelf Mills, the bitumen mix is the part of the process over which there is the greatest internal control.

The process flow diagram (figure 3.4) shows the transportation and processing of the current bitumen mix, including the heating and conveying of the current virgin feedstock. The feedstock is limestone that has been quarried, crushed and sieved before being delivered to the external storage bunker. Other particle sizes remaining from the sieving process are used in other industries such as the ceramics industry.
Figure 3.4. Internal feedstock conveyor system

The composite line diagram in figure 3.5 illustrates the speeds of the conveyors. The bitumen is delivered and then stored in an external storage tank at elevated temperature. The limestone is also stored in an external storage bunker (tank D on the far right of the diagram) before being drawn internally to the colt limestone storage bunker using a series of air blowers (shown to the right of the diagram). It is then heated and conveyed to bunker 1 (SB56) shown in figure 3.4, where the limestone is held at around 150 °C. The aeromechanical conveyor draws the limestone upwards at an approximate rate of 2600 kg/hr. This conveyer is insulated in order to try to maintain the elevated limestone temperature. Moisture can then be driven off at the top vent.
Figure 3.5. Line diagram showing external tanks used to store limestone on the right hand side leading to the internal tanks used to store and heat the limestone on the left hand side.
A system of air blowing is used in an effort to ensure that the material does not stagnate and settle. At this point in the system there is a vibratory probe, LT56, which measures the mass of material in the bunker. The screw conveyor is driven by motor M57, which moves material into bunker 2 (WB58).

Bunker 2, the weighted bunker, is designed to hold 210 kg of material that will be dosed into the mix, with a margin of 40 kg. A load cell accurately measures the amount of material.

The applicators draw a bitumen mix from the compound tank, CT30, at a rate that will depend on the backing weight, face yarn type and construction, line speed and a number of other variables.

The level of material in CT30 is measured using a radioactive probe. At low level, a signal is sent for the compound mixer, CM28, to dump another load into the tank. After the load is dumped, the CM then needs to begin mixing another batch. The pre-modified bitumen begins to enter the CM before the dosing screw begins to draw off the 210 kg in WB58.

WB58 will then refill by drawing off material from SB56 via the screw conveyor and the system is supplied again.

A photograph of the internal limestone storage and conveyance equipment is shown in figure 3.6.
As commented earlier, it was perceived that there was a problem with the arrangement such that the process was not producing the bitumen mix at a fast enough rate. It was intended that the backing line would back and produce carpet tile at a rate of 10 m/min. In order to calculate how fast the mix must be, the material composition must first be considered. A sample was taken from the process without face yarn of 100 cm$^2$ and mass 31.49 g. This equates to a mass per unit area of 3149 g/m$^2$.

The composition of the backing for this carpet-type was two sheets of fibreglass of total mass 69.90 g/m$^2$ and one polypropylene sheet of mass 45.00 g/m$^2$.

Therefore the bitumen mix made up 3034 g m$^{-2}$. Of this nominally two thirds was limestone, i.e. 2023 g m$^{-2}$, the remaining one third was pre-modified bitumen.

Since the material is 2 m wide, in order to achieve a line speed of 10 m/min, corresponding to 20 m$^2$/min, limestone must flow at $20 \times 2023 = 40.5$ kg/min.
If a batch size is 210 kg, then the weighted bunker, WB58, must empty and fill in a time of $210/40.5 = 5.18\text{ min}$, i.e. 5 minutes and 11 seconds.

If this time can be achieved successfully during typical processing conditions, then it will be known that the mix can deliver a line speed of 10m/min and it will no longer be a hindrance to performance.

If the progress of the mix from applicators back to delivery point is followed, it can be seen that the parameters of the process that can be controlled are:

At the applicators:

- Weight and tension of fibreglass
- Weight and tension of polypropylene
- Transverse movement of top cloth
- Line speed
- Tension of top cloth and completed carpet construction
- Distance between rollers

At the compound tank:

- Speed and power of motor drawing off bitumen mix

At the compound mixer:

- Temperature of thermal oil surrounding mixing tank
- Duration of mix

At the bitumen tanks, kept hot from delivery:

- Thermal oil jacket surrounding tank controls hold temperature of bitumen
- Number of cycles in system contributes to temperature control as there is only insulation and no heating arrangement in the tanks. Less cycles result in a temperature drop over the time that the mix is held.

At the storage bunkers:

- Start fill level of bunker
- Stop fill level of bunker
- Thermal oil temperature of jacket surrounding bunker
- Maximum air pressure for agitation of storage material
- Length of time air is blown into the storage bunkers under pressure
If these parameters can be controlled successfully, it may be that the material flow required can be achieved. Anecdotal evidence from the line operators suggested that there was variation in batches of material due to differences in the material delivered. However, a large amount of research was undertaken (Carter, 2004) that showed there were no significant variations in the material delivered and that conditions did not have a consequential effect on movement of filler material within the system. Therefore, the next step in this investigation is to analyse the various parts of the process and their controls in order to reduce the amount of time taken to move the bitumen mix to the applicators.

### 3.2.2 Analysis of Different Parts of the Process

#### 3.2.2.1 Bunker Profile

It has been identified that the critical movement of limestone material in the system is from the heated storage bunker, SB56, to the weighted bunker, WB58, and consequent dosing from WB58 to the compound mixer, CM28.

It was decided initially to assess whether mass flow could be maintained through the bunkers without assistance from further agitation methods. The results from crude initial experiments, included in the 6-monthly report (Carter, 2004), showed that the material did not flow readily.

Shear strength tests were carried out using an Ajax vertical shear cell. Wall friction tests using an Ajax long stroke translational device were performed on a stainless steel plate with a 2B finish.

The friction angle was determined to be 25.1°, which resulted in a suggested minimum angle of 73.1° for a conical hopper and 63.1° for Vee hopper design, as recommended by the British Materials Handling Board (Ajax, 2004).

SB56 has an angle at the base that was considerably less than that required. It was noted that agitation was required in order to move material readily through the system. However, changing the complete hopper design was deemed inappropriate and too costly. Therefore the designed method of agitation within SB56 was examined and modified.

#### 3.2.2.2 Agitation within Storage Bunker

In the current set-up, the heated storage bunker 1, SB56, utilises blown, dried air to agitate material inside. A schematic is shown in figure 3.7. This method was proving ineffective with blockages reported frequently and material obviously building up around the edges of the hopper.
**Figure 3.7. Schematic of aerator design**

Experiments were conducted in order to assess the packing of the virgin feedstock that was to be expected during normal operations and to relate this to the blockages reported. The samples were sieved into a container to produce a known volume and the mass found—this is known as the untapped volume. The samples are then tapped a number of times until the volume of material reduced. The results showed that from a loose packed density of around 900 kg/m³, after sieving through a brass sieve of 500 μm, the density of the limestone could increase to around 1400 kg/m³ with tapping. This can increase by a further 4% over time without further agitation. The average of 5 results is shown in the table below.

<table>
<thead>
<tr>
<th>Initial untapped volume</th>
<th>Tapped x 60</th>
<th>Tapped x 90</th>
<th>Overnight</th>
<th>4 Days</th>
</tr>
</thead>
<tbody>
<tr>
<td>898</td>
<td>1142</td>
<td>1386</td>
<td>1394</td>
<td>1441</td>
</tr>
</tbody>
</table>

*Table 3.1. Results from tapping experiments showing an increase in powder bulk density (kg/m³)*

It follows from this that the method of agitation in SB56 should introduce as little vibration to the material as possible.

Upon investigation of the hopper, it was discovered that during a clear-up process, designed to remove the compacted material at the edges of SB56 by mechanical means, the pads providing the air blown system had become damaged. The pads were aerators designed to blow air into the virgin feedstock at low pressure in order to facilitate its flow. When the aerators were replaced, there was an immediate improvement in flow. This showed that poor maintenance of the equipment is critical to this performance issue.
The extent of this improvement was assessed and the optimum time of aeration and maximum pressure of the aerators evaluated experimentally. At a line speed of 8.1 m/min (variable), these parameters were altered for a minimum of 45 minutes in order to observe any variation in the flow rate of material from WB58. All other parameters remained the same.

The pressure of the air applied through the aerators could only be varied from 0.6 bar to over 1 bar, due to machinery constraints. This was therefore attempted at intervals of 0.1 bar. The time on:off of 4:0 indicates that the air was continuously applied, 1.5:9 indicates that the aerators are on for a very small fraction of time. A time of 4.5:1.5 indicates that the aeration was applied for 75% of the time and 10:1 approximately 90%.

The results showed that over the range of parameters investigated (table 3.2 and 3.3), a pressure of 0.6 bar and time on: time off of 4.5 seconds: 1.5 seconds offered the least time of fill and empty of WB58.

<table>
<thead>
<tr>
<th>Pressure (bar)</th>
<th>Average Empty (min:sec)</th>
<th>Average Fill (min:sec)</th>
<th>Total (min:sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.9</td>
<td>02:29</td>
<td>04:18</td>
<td>06:47</td>
</tr>
<tr>
<td>0.8</td>
<td>02:29</td>
<td>04:34</td>
<td>07:03</td>
</tr>
<tr>
<td>0.7</td>
<td>02:26</td>
<td>03:47</td>
<td>06:13</td>
</tr>
<tr>
<td>0.6</td>
<td>02:29</td>
<td>03:14</td>
<td>05:44</td>
</tr>
</tbody>
</table>

Table 3.2. Effect of variation in air pressure of aerators on average empty and fill times of WB58 (time on: time off set at 4.5:1.5)

<table>
<thead>
<tr>
<th>Time On: Off (sec)</th>
<th>Time On (%)</th>
<th>Average Empty (min:sec)</th>
<th>Average Fill (min:sec)</th>
<th>Total (min:sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4:0</td>
<td>100</td>
<td>02:25</td>
<td>03:20</td>
<td>05:45</td>
</tr>
<tr>
<td>10:1</td>
<td>91</td>
<td>02:30</td>
<td>03:59</td>
<td>06:29</td>
</tr>
<tr>
<td>4.5:1.5</td>
<td>75</td>
<td>02:30</td>
<td>03:14</td>
<td>05:44</td>
</tr>
<tr>
<td>4:4</td>
<td>50</td>
<td>02:27</td>
<td>03:25</td>
<td>05:52</td>
</tr>
<tr>
<td>1.5:9</td>
<td>14</td>
<td>02:28</td>
<td>03:40</td>
<td>06:08</td>
</tr>
<tr>
<td>0:4</td>
<td>0</td>
<td>02:27</td>
<td>04:38</td>
<td>07:05</td>
</tr>
</tbody>
</table>

Table 3.3. Effect of variation in time on: time off of aerators on average empty and fill times of WB58 (air pressure set at 0.6 bar)
With the changes made to the aerators, it was shown that the time of transport of a full cycle of virgin feedstock into and out of WB58 could be reduced to 5 minutes 44 seconds- a reduction of 25% on the original timings of over 7 minutes without aeration.

It is therefore shown that changing the method of agitation in SB56 increases the flowability of the virgin feedstock and consequently its movement into WB58 and reduces the time needed for each mix. Other methods of reducing the time to fill and empty WB58 were then investigated.

The mass transferred from WB58 to the CM is fixed at 210 kg per mix, as this is the maximum capacity of the CM. Throughout previous experiments it has been shown that the transfer of virgin feedstock from WB58 to the CM takes approximately 2 minutes 30 seconds, i.e. a rate of 1.4 kg/s. The design of the dosing screw indicates that a rate of 3.1 kg/s could be achieved in principle.

The fill and empty trigger levels of the bunker are such that it begins to fill at 200 kg and reaches high level at 232 kg. Therefore there is little scope for variation in the emptying of this bunker, as it needs to be filled as soon as possible. Observing the measurements from the probe in WB58 (recorded as WT58), it was seen that the bunker always reduces to a very low level and therefore changing the fill levels would have little effect.

However, in the course of usual operations, the perception of the operators is that in order to increase the amount of material flow through the system, the storage bunker SB56 should remain as full as possible. Results from the probe recordings, LT56 within SB56 show that SB56 continuously contains material.

As WB58 begins to empty (shown by WT58 decreasing in figure 3.8 overleaf), material moves into the CM through the dosing screw. Once WB58 has released the appropriate amount of material, it can begin filling again. As the screw conveyor begins to move material from SB56 to WB58 it can be seen that LT56 begins to drop as WT58 increases. The aeromechanical conveyor draws material into SB56 as the low fill level of SB56 is reached. At the maximum fill level of WB58, WT58 is again at its maximum, whilst LT56 is at minimum. The aeromechanical conveyor continues to draw material into SB56 and so LT56 continues to rise to its maximum fill level. It is at this point that the aeromechanical conveyor will cease to draw any more material and the fill level remains constant until more material is required.

When the valves open to the conveyors, a backpressure results that causes a false positive reading on the probes. The extra peaks at the top of the chart (Figure 3.8) illustrate this.
At a line speed of 7.5 m/min the begin fill and stop fill levels of SB56 were altered in order to try to decrease the fill time of WB58. The settings were kept for a minimum of 30 minutes and results shown below.

<table>
<thead>
<tr>
<th>Range (kg)</th>
<th>Empty Time (min:sec)</th>
<th>Fill Time (min:sec)</th>
<th>Total (min:sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Begin fill-stop fill</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>210-220</td>
<td>02:27</td>
<td>03:51</td>
<td>06:18</td>
</tr>
<tr>
<td>125-150</td>
<td>02:24</td>
<td>03:36</td>
<td>06:01</td>
</tr>
<tr>
<td>125-140</td>
<td>02:28</td>
<td>03:28</td>
<td>05:56</td>
</tr>
<tr>
<td>130-145</td>
<td>02:26</td>
<td>03:17</td>
<td>05:43</td>
</tr>
</tbody>
</table>

Table 3.4. Effect of changing fill and empty levels of SB on fill and empty times of WB.

Table 3.4 shows that by reducing the amount of virgin feedstock remaining static in SB56 the fill time of WB58 can be reduced by 35 seconds.

Figure 3.8. Graph showing fill and empty levels of SB56, shown by the probe LT56, and effect on fill and empty levels of WB58, shown by the probe WT58

Figure 3.8 shows that SB56 is fully empty for approximately 1 minute and 30 seconds consistently. During this time, material is flowing directly from the slower aeromechanical conveyor to the screw conveyor. Therefore the demand is greater than the supply and the system is not performing at its optimum.
Taking the above sample, it can be seen that if the correct adjustments can be made to SB56 so that it empties to a minimum every time (a reduction of 1 minute 30 seconds of direct transfer from the slower aeromechanical conveyor at 0.72 kg/s to the screw conveyor at 1.2 kg/s), then the fill time of WB58 can be further reduced.

The mass of material that is transported from the slower aeromechanical conveyor over this time of 1 minute 30 seconds is 64.8 kg. If it were direct from the screw conveyor, the time taken for this amount to be transported would be 54 seconds. Therefore a further 36 seconds could be saved if the material during this time were direct from SB56 to WB58 and not from further back in the system to WB58.

Therefore, if the system is set up to enable SB56 to empty fully and then to refill at the same time as WB58 is emptying, the cycle time can be reduced from the observed time of 5 minutes 43 seconds to 5 minutes and 7 seconds. This is within the time limit of 5 minutes 11 seconds required.

3.2.2.4 Hold Time of Material in Bunkers

It has been shown that the shorter the period of time for which the virgin feedstock remains static, the more efficiently it will flow through the system and into the CM. The length of time for which the material is static will depend on three factors, i.e. the maximum fill level, the minimum fill level and line speed. If the line speed is low, then the fill levels of SB56 need to remain low, in order that WB58 fills slowly and the virgin feedstock remains stagnant for the minimum time. These adjustments were taken into consideration when specifying the operating conditions.

3.2.2.5 Performance of Modified System

During the course of this investigation, the inverters attached to the motors which drive the aeromechanical conveyor taking material from the external storage bunker to SB56, the screw conveyor taking material from SB56 to WB and the dosing screw taking material from WB58 to the CM were adjusted in order to try to increase the material movement throughout the system. Data recorded at a line speed of 10 m/min (Table 3.5) showed that the motors had increased the delivery rates of the aeromechanical conveyor and screws by a small margin, even though SB56 did not empty fully again.
Table 3.5. Differences in rates of material transfer by conveyors and screw before and after motor improvement

<table>
<thead>
<tr>
<th></th>
<th>Aeromechanical conveyor (kg/s)</th>
<th>Screw conveyor (kg/s)</th>
<th>Dosing screw (kg/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Before</td>
<td>0.80</td>
<td>1.05</td>
<td>2.40</td>
</tr>
<tr>
<td>After</td>
<td>0.85</td>
<td>1.08</td>
<td>2.80</td>
</tr>
</tbody>
</table>

With the range of modifications in place a 10m/min line trial was conducted. It showed a consistent fill time of WB58 of 3 minutes 14 seconds and empty time of average 1 minute 15 seconds. This total cycle time of 4 minutes 29 seconds is well below that required in order to achieve the specified line speed of 10m/min.

As the line could now perform as specified, using the virgin feedstock, a replacement candidate could now be assessed and possibly trialed.

3.3 Introduction of Alternative Backing Filler Material

3.3.1 Background and Scope

It was thought originally that batch-to-batch variations in material properties of the virgin feedstock were responsible for the perceived ‘bottle-neck’. However, it has been shown in the previous section that adjusting the processing parameters can compensate for any changes that result from material differences. A further part of this investigation was to assess the changes in material properties of the virgin feedstock throughout normal processing and complete a comparison with recycled feedstock.

A potential new feedstock, LF_01, was sourced from the waste stream of the aggregates industry. The source of the material is described in section 3.3.2. It was considered as a first option in order to assess the range of properties that may affect its flow and transportation. The material characteristics were assessed and compared to the current virgin material. LF_01 was sieved using an industrial process that was sourced externally to InterfaceFLOR and compared to the as-received LF_01 sample.

This investigation would lead to material parameters required from further recycled feedstock candidates. Recent trials with this first recycled feedstock indicate that processing parameters can be altered to compensate for limited material changes. The recycled feedstock was introduced to the system at the heater and conveyor before the internal heated storage bunker, SB56. It then flowed through the conveyors and bunkers and continued in the normal process cycle to the applicators in the bitumen mix, where it was applied as part of the backing system.
The characteristics of the filler affecting processing can be dependent on their source and this is described in the next section.

3.3.2 Source of Filler

In late 2003, InterfaceFLOR identified a possible source of post-industrial recycled limestone from LaFarge Aggregates. The material that InterfaceFLOR would receive from LaFarge is produced as a result of their manufacturing process for aggregates. This material is currently sent to landfill and is therefore classified as waste (Environmental Protection Act, Section 75, 1990). Since this material will be used in a different industry it has been classified as pre-consumer recycled material (Wrap, 2007).

The mix of material used at LaFarge Aggregates will depend on the requirements of the customer. Harder material such as ‘grit stone’ and glass is often used in applications that require greater wear, for example road-surfacing.

The LaFarge Ashbury plant uses approximately 60 wt% limestone, 38 wt% ‘grit stone’ and 2 wt% recycled glass. This ratio of material can be used to approximate the ratio of material found in the dust material. Section 3.3.3 describes the exact ratio of chemical components that make up the filler.

The glass portion of the material is post-consumer waste and arises from bottle banks. However, this material is not sorted at a recycling centre and arrives at LaFarge as received. Therefore the consistency of material is reliant on consumers being selective about their recycling and sorting material correctly.

The photograph (Figure 3.9) below shows the mix of material that is then ground and used in the process. It can be seen that this mix of material includes plastic bottles as well as general refuse such as tins. It therefore follows that waste should be properly separated in order to be recycled more effectively. Figure 3.10 shows the resulting material that is used as aggregate in the LaFarge process.
Figure 3.9. Mix of material that is used as glass in the aggregate making process

Figure 3.10. Ground glass material to be used in aggregate manufacturing process
The mixture of material that is received by InterfaceFLOR will vary depending on the mixture of material that has been required by the LaFarge customers, although it will approximate to those values given above.

The material is fed into a system of hoppers (shown in figure 3.11) where it is stored for a short period of time before being demanded by the system.

*Figure 3.11. Feed system for LaFarge Ashbury aggregate manufacturing plant*

The process by which the material is produced by LaFarge aggregates is shown in figure 3.12 and then schematically in figure 3.13. The bag filter on the top right hand side of the diagram is used to store material before it is sent to InterfaceFLOR.
Figure 3.12. Photograph of aggregate manufacturing facility
Figure 3.13. Manufacturing process for LaFarge aggregates

Wheeled loaders take material from around the site and feed the system on the left hand side of the diagram, shown above. The origin of this material varies by site.

The graded material is mixed according to customer specification, fed into the conveyor and then transported to the dryer. At the dryer the material is agitated, producing large volumes of powdered material. This is extracted via the skimmer to a set of bag filters. It is here that the excess powdered material is stored. This is the material that is sent to InterfaceFLOR for use as filler.

The dried aggregate is then screened according to size and mixed with the bitumen as required by the customer recipe. The aggregate mix is then either stored for future use or transported for immediate use.

It should be noted that this ratio of inputs is not guaranteed and, hence, there will be variation between batches. The material characteristics will therefore also be variable. However, each input can be considered in turn. The three most important characteristics of an individual particle indicating its capacity for flow are its shape, size and composition (Coulson and Richardson, 1999). The material characteristics are considered below.
3.3.3 Material Characteristics

3.3.3.1 Chemical Composition

Several samples of the filler, taken from deliveries made during the trial weeks in late Feb and early March 2006, were sent to Ch Zah at Interface Research and Development and examined using a Scanning Electron Microscope (SEM). The samples were fused as metal oxide then acid digested to Inductively Coupled Plasma (ICP) metal test. The results are shown in table 3.6 below.

<table>
<thead>
<tr>
<th>Identification</th>
<th>Al₂O₃ (Wt %)</th>
<th>SiO₂ (Wt %)</th>
<th>SO₃ (Wt %)</th>
<th>MgO (Wt %)</th>
<th>TiO₂ (Wt %)</th>
<th>Fe₂O₃ (Wt %)</th>
<th>CaCO₃ (Wt %)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alloy or Spec. Req.</td>
<td>(1)</td>
<td>(1)</td>
<td>(1)</td>
<td>(1)</td>
<td>(1)</td>
<td>(1)</td>
<td>(2)</td>
</tr>
<tr>
<td>2-3-06</td>
<td>8.5</td>
<td>36.4</td>
<td>2.8</td>
<td>2.3</td>
<td>0.5</td>
<td>3.2</td>
<td>46.3</td>
</tr>
<tr>
<td>6-3-06</td>
<td>11.4</td>
<td>54.3</td>
<td>3.0</td>
<td>2.8</td>
<td>0.7</td>
<td>4.6</td>
<td>23.2</td>
</tr>
<tr>
<td>9-3-06</td>
<td>9.2</td>
<td>38.7</td>
<td>2.6</td>
<td>2.3</td>
<td>0.6</td>
<td>3.8</td>
<td>42.8</td>
</tr>
<tr>
<td>28-2-06</td>
<td>8.3</td>
<td>36.4</td>
<td>2.0</td>
<td>2.0</td>
<td>0.5</td>
<td>2.8</td>
<td>48.0</td>
</tr>
</tbody>
</table>

*Table 3.6. Results of ICP elemental analysis (Ch Zah, 2006)*

The analysis showed that the material was a blend of limestone, silica and other metal oxides.

Samples of the Ashbury-LaFarge material were previously viewed using a SEM at The University of Surrey and these test results were similar to those given above. Analysis was carried out in December 2003, the description of which can be found in the 6-month report attached to this portfolio (Carter, 2004). The analysis yielded the following data.
In comparison to the virgin filler, which is almost exclusively CaCO$_3$ (Carter, 2004), LF_01 contains up to 55% silica based stone particles. LaFarge blend the limestone (of Derbyshire origin) with ‘grit’ stone (a silica based aggregate) at the site along with the glass recyclates (see figure 3.11 above).

This silica based aggregate is significantly harder than limestone with the grit stone having almost double the polished stone value (PSV). The PSV of virgin filler is around 36 PSV whereas LF_01 has a value of 65 PSV. Although these figures relate to larger particle sizes of material (approximately 10 -15mm) and were developed to measure the slip resistance of roadways, it is clear that the increased hardness of the stone will have some affect on the hardness and abrasiveness of the bitumen backing when loaded with this material in comparison to the virgin material.

As the proportion of ‘grit’ stone can vary between 35 and 55 wt% the backing hardness could vary between 25 and 50 % (based on empirical calculations and allowing for experimental error). PSV is measured using BS:812 – this standard also covers aggregate abrasion value (AAV), which may be of more use in calculating its impact on the tile cutting process.

It was therefore deemed that only a full-scale trial would be useful in determining if the compositional changes in material would adversely affect processing. However particle shape is also a useful indicator of flow properties and this is considered in the next section.

### 3.3.3.2 Particle Shape

SEM analysis was conducted showing the particles from recycled and virgin feedstock are irregularly shaped. The virgin feedstock tends to be more a reasonably regular cuboid shape and the recycled feedstock appears to be more elongated. This tends to lead to poor flowability (Coulson and Richardson, 1999).

<table>
<thead>
<tr>
<th>Composition</th>
<th>Al$_2$O$_3$</th>
<th>SiO$_2$</th>
<th>SO$_4$</th>
<th>MgO</th>
<th>TiO$_2$</th>
<th>Fe$_2$O$_3$</th>
<th>CaCO$_3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wt %</td>
<td>11.2</td>
<td>35.5</td>
<td>2.2</td>
<td>2.8</td>
<td>0.6</td>
<td>4.9</td>
<td>42.5</td>
</tr>
</tbody>
</table>

*Table 3.7. Results from SEM analysis (Carter, 2004)*
Figure 3.14. SEM analysis showing virgin material

Figure 3.15. SEM analysis showing larger particles from LF_01
Analysis of particle shape could only ascertain that the replacement candidate appeared to come from cleavage-type fractures. Both the virgin and replacement samples were assessed to be poor shapes for flow.

### 3.3.3.3 Particle Size

Extensive investigations were carried out regarding particle size. Samples of the recycled feedstock were taken before and after processing through the aeromechanical conveyor and compared to the virgin feedstock standard. The analysis of particle size was conducted using a series of mechanical sieves in order to attain groups of particles within a size range, shown in the table below.

<table>
<thead>
<tr>
<th>Type</th>
<th>Particle size distribution (%) microns</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>&gt; 300</td>
</tr>
<tr>
<td>Un-sieved - As received</td>
<td>2.20</td>
</tr>
<tr>
<td>Un-sieved - After screw</td>
<td>0.37</td>
</tr>
<tr>
<td>Sieved - As received</td>
<td>0.08</td>
</tr>
<tr>
<td>Sieved — After Screw</td>
<td>0.00</td>
</tr>
<tr>
<td>Virgin Feedstock</td>
<td>0.05</td>
</tr>
</tbody>
</table>

*Table 3.8. Sieve analyses of recycled feedstock (LF_01), before and after sieving compared to standard virgin material*

The analysis shows that there are larger particles present in the recycled feedstock when un-sieved. It is thought that these particles may cause tearing of the fibreglass backing when they arrive at the applicators as they get trapped between the rollers and backing and are scrapped along. However, only a full-scale trial would indicate if this was the case.

### 3.4 Full-Scale Trial

#### 3.4.1 Introduction

A full scale trial was undertaken in order to assess the material under actual processing conditions. The replacement material was used in the two conditions shown above; as received and sieved. The material was introduced using a series of blowers into the system at the heater and conveyor before the internal heated storage bunker, SB56. It then flowed through the conveyors and bunkers and continued in the normal process cycle to the applicators in the bitumen mix, where it was applied as part of the normal backing system.
3.4.2 Moisture Content

Moisture is introduced into the sample below 70°C. This moisture will not cause visual changes to the material (the previous SEM analysis showed this), but will probably interact with the limestone causing it to become more ‘sticky’ and difficult to flow. The current processing conditions can drive off moisture effectively to below 0.3%, but this can vary throughout the manufacturing day.

Comparing the moisture in the materials after the aeromechanical conveyor shows that the candidate materials contain considerably more moisture at any given time (See below).

<table>
<thead>
<tr>
<th>Type</th>
<th>Normal</th>
<th>Sieved</th>
<th>Un-sieved</th>
</tr>
</thead>
<tbody>
<tr>
<td>Moisture (%)</td>
<td>0.075</td>
<td>0.25</td>
<td>0.11</td>
</tr>
</tbody>
</table>

*Table 3.9. Moisture variation during trial*

However, monitoring of the virgin material at the vent in SB56 has shown that moisture can vary considerably with processing, compensating for these changes. Therefore, it is believed the processing changes can compensate for any changes in material properties encountered.

3.4.3 Bitumen Mix

The greater number of smaller particles in the LF_01 material may cause an increase in viscosity of the bitumen mix. This is because they will have a greater surface area per unit mass than a larger particle size which will in turn interact with the liquid bitumen. Samples were taken from the applicators during the trial and compared to the standard bitumen mix made with virgin feedstock.

Samples were taken from the compound tank and compared to the standard mix, using BS 13302. Mixes 2 to 4 were the sieved feedstock, 5 to 7 were the un-sieved feedstock and 1 and 8 were mixed with the standard feedstock in an unknown proportion.
<table>
<thead>
<tr>
<th>Mix</th>
<th>Virgin Feedstock</th>
<th>Recycled Feedstock</th>
</tr>
</thead>
<tbody>
<tr>
<td>% Filler</td>
<td>69.52</td>
<td>69.65</td>
</tr>
<tr>
<td>150°C</td>
<td>103.0</td>
<td>126.0</td>
</tr>
<tr>
<td>155°C</td>
<td>83.8</td>
<td>96.0</td>
</tr>
<tr>
<td>165°C</td>
<td>60.8</td>
<td>65.0</td>
</tr>
</tbody>
</table>

*Table 3.10. Viscosity changes of bitumen mix during trial measured at elevated temperature (Pa.s)*

This data shows clearly that the candidate for replacement filler possesses viscosity at the upper end and beyond of the standard specification of 80-150 Pa.s at 150°C as defined by InterfaceFLOR. The unsieved material contains larger particles for this process. This is reflected in the slightly lower viscosity measured, in comparison with the sieved samples. Therefore there will be a careful balance required between removing large particles that may interfere with the application of bitumen and reducing the number of small particles that may adversely increase the viscosity of the mix. However, this level of 25 wt% of particles below 75 μm appears to be the maximum within which the process controls may compensate for.

The temperature of the standard bitumen mix applied has been varying by approximately 10°C, thus increasing the viscosity. If the recycled feedstock can be heated to the original temperature then the viscosity can be reduced to an acceptable level.

### 3.4.4 Trial Conclusion

The full scale trials showed that the material (LF_01) could be used successfully as a replacement filler material in the bitumen mix provided process controls can be altered to compensate. Evidence from the trial indicates that few problems were encountered, except for a number of short draglines at the application of the bitumen mix to the backing system. Therefore it was decided that the recycled feedstock could potentially replace the virgin feedstock based on particle size. However, there were some complications with the filler.
As explained previously at the end of the carpet tile manufacturing process, the rolls of material are cut into tiles. A large press with blades is currently used to do this. During the trial the tile-cutting blades had to be re-sharpened after just 15-30,000 cuts compared to 500,000 using the virgin filler. InterfaceFLOR, US, has confirmed that the filler they use has very high silica content (around 62%) and change their blades approximately every 10,000 cuts.

It can be concluded that the relatively small increased in hardness of the filler material has a significant impact on the lifetime of the cutting edge. The more frequent blade changes will have a time and cost implication that may have a detrimental effect on production and should be considered against the environmental benefits of using alternative filler.

3.5 Summary

A significant barrier to the introduction of recycled feedstock was that the processing line was already running below optimum speed using virgin material of known and consistent characteristics. The bottlenecks in the transport of material from storage to the processing line were examined and identified. This involved the use of ‘soft’ evidence such as anecdotal evidence from line operators to guide the investigation, although ultimately conclusions were drawn from observation and measurement. Solutions were found to these bottlenecks and implemented such that a constant line speed improvement of some 25% was achieved.

The recycled feedstock was assessed for parameters affecting flow, such as particle size, shape and composition. This data, combined with the increased confidence in processing, allowed full-scale trials to be carried out which demonstrated that an acceptable line speed could be maintained using this feedstock. These experiments also indicated the range of properties that would be required in other recycled feedstock. The feedstock will be required to be a chemically inert material with particles regularly-shaped. Ideally these particles would have a normal distribution below 300 μm and less than 25 wt% of particles below 75 μm.

This result means that the virgin feedstock can be substituted in the process with confidence in the machinery, process and method. As a consequence the substituted material could be from a recycled source, and when used in conjunction with InterfaceFLOR’s recycled face yarn this results in an immediate increase to over 70 wt% recycled product content. This has satisfied in part the phase 1 objective of this project to be able to reduce environmental impact of current product and continue the progress already undertaken at InterfaceFLOR. On the conclusion of this part of the project, there was a change in the direction of the company which led to the second phase of this project and this is described in the next chapter.
Chapter 4 Innovation Concept

4.1 Introduction

One way in which a product can become more sustainable is by replacing virgin feedstock with recycled material. This has been achieved at InterfaceFLOR and has been described in the previous chapter. The company has also investigated and are continuing to examine other ways of introducing recycled content into their current product - including the possibility of recycled nylon or polypropylene yarn. This evolutionary process, led by the Product Development Teams, has proven successful in getting InterfaceFLOR to the current state which has been described in Chapter 1.

InterfaceFLOR requires revolutionary changes to bridge the gap between the status quo and the requirement to be fully sustainable. The role of Innovations Director and the Innovations Department was created in order to address these challenges. As well as leading the creation of new concepts, this group has the responsibility for bringing an Innovations Pipeline of ideas and products to market.

As part of the brief for the Innovations Department, the Innovations Workshops were established, as described in section 1.3.3.3. The formation of the network formed a turning point for InterfaceFLOR as well as the change in direction of this EngD project to the commencement of phase 2.

A number of novel concepts for redesigning flooring were suggested by the ‘Innovations Network’, some of which have since been developed further to prototype stage. One such concept was described as ‘Pour Man’s Floor’ - a system of liquid material from renewable sources that could be poured onto a floor and set quickly. This concept ultimately became known as Pour-A-Flor (PAF) and this is described in more detail in the next section.

The PAF concept brief was defined as part of this project. A literature and market search indicated that there was no immediate solution to the brief. It was decided therefore to define an intermediate material which could act as a PAF prototype. This could give some indication as to whether the final concept was viable. The prototype requirements and the screening of candidate systems are described in section 4.3.
A resin material, based on epoxidised linseed oil (ELO), was suggested by leading researchers as a candidate system. This system was investigated further, in order to assess if the material had potential to fulfil the defined prototype requirements and described in section 4.4. This EngD project provided the impetus for this investigation and guided the research for this part.

PAF spawned a number of other creative ideas linked to the original concept. These have been continued as part of this EngD project and are described in section 4.5. In this section the other possible projects that could be satisfied with this ELO-based resin material are described- renewable Interlock (previously described in section 2.2.2.3) and a replacement backing system (introduced in the previous chapter). The investigation of the ELO-based resin material for these concepts as part of this EngD project is described in the next chapter. The original PAF concept is described in the next section.

4.2 PAF Concept Description

The following section describes the ideal characteristics of the PAF system. This brief was constructed by ignoring the limitations of present materials and only considering ideal characteristics of the concept. The brief is entirely without constraints.

PAF is a multipart and modular system. The concept offers flexibility with creativity as the floor is literally poured either onto an existing surface or a new design. PAF is a design-upwards system, in that it encourages the customer to begin to create a room from the base upwards and consider the floor as a major design tool.

The underlay, or design substrate, that constitutes the design of PAF offers a range of possibilities. It provides the visual mood for the surface as it provides design flexibility in colours, shapes, patterns and brand identity. InterfaceFLOR would suggest design ideas and sell templates for use within PAF to encourage individual customer creativity, whilst highlighting other areas of sustainability.

The top surface for PAF will be provided in a one or two-part system that can be purchased off-the-shelf as a liquid. The floor will be designed to set-to-touch quickly (2 hours maximum) and to harden for contract use within a designated time (6 hours maximum). The PAF will be self-levelling and offers a hygienic seal for the floor, whilst incorporating anti-slip elements, which will be designed to be an impervious barrier to water and micro-organisms, so making PAF ideal for wet areas.
The floor is easy to clean, as the surface can be rough or textured (which could be achieved through the addition of particles into PAF), unlike textile surfaces. The surface can be vacuumed and mopped using conventional methods without damage to the surface.

PAF could be removed from the substrate either chemically or mechanically. It could then be placed in a composting facility to biodegrade over a period of time, or placed in a home composting facility to degrade over a prolonged period.

The PAF concept is positioned at the top of the waste hierarchy in that it generates no waste at installation, since the amount of material required is precisely delivered. It is also made from entirely renewable resources and is completely biodegradable. Therefore the material taken from the Earth when PAF is made is returned in a usable form.

Collaborations and partnerships were identified as essential to implement this concept. InterfaceFLOR required external partners to provide technical assistance and to provide initial biopolymer material. Technical assistance would also be required from academic partnerships to assess the structure and surface chemistry of the PAF prototypes. The external partners could also assist the company in the advancement of the prototypes through to small-scale production phase.

In summary the ideal characteristics of the PAF system are that it:

- Is a one or two part system
- Is made entirely from renewable resources
- Can incorporate other material as a sub-floor to provide designs that will be possible for the home-user to use
- Is simple to install- including setting and hardening quickly
- Offers an impervious barrier to liquids and micro organisms found in everyday use
- Is easy to clean
- Is versatile enough to be used in many climates.
- Is entirely biodegradable
The concept description shown above is an ideal situation that would require years of research and development in order to move to production scale. The first six months of this project were spent defining the concept brief and establishing partnerships in order to acquire the relevant expertise. Agrotechnology and Food Innovations (A and F) were identified as a leading biopolymer research organisation that could provide valuable input to this project. InterfaceFLOR had previous contact with A and F through the biopolymer.net network on a consultancy basis. They had previously been proficient in areas that were appropriate for the PAF concept.

To this end A and F suggested a primary technology that was investigated as part of this project and conducted the research into drying times of the ELO-based resin material under the direction of the research engineer.

In order that a prototype could be developed, the second phase of the project was further divided into 4 tasks:

1. Translation of the PAF concept into quantifiable properties
2. Screening of available casting technologies
3. Proof-of-principle A and F technology
4. Feasibility of other systems

The translation of PAF into measurable properties enables a comparison of the concept requirements with those that are currently available from products in the marketplace. This then led to the definition of the prototype requirements, described in the next section. Available casting technologies were examined and a patent search completed to assess if any product currently available fulfilled the prototype requirements. The second phase of the project concentrated on the ELO-based resin material suggested by A and F. This investigation is described in the next section.

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2 Agrotechnology and Food Innovations describe themselves as specialists in market-driven research for the food sector and agrotechnology. It is a modern research and development facility, focusing on the entire supply chain and works in partnership with Wageningen University. Its key activities are in bio-based products, quality in the supply chain, food quality, agrisystems and the environment. It can offer research facilities that range from the lab to pilot-scale facilities.
4.3 Translation of PAF to Measurable Properties

4.3.1 Prototype Definition

As previously described, one of the first tasks was to translate PAF into measurable properties in order that the prototypes could be assessed against a standard. It was not intended that the prototype requirements would be those of the final product, but would be those of an intermediary that could be refined to fulfil the PAF concept requirements. This ensures that options remain open for the first stage of this project, as properties can be refined through experimental evaluation and assessment. In order to define the prototype requirements, a number of tasks had to be completed first. These are shown in figure 4.1.

*Figure 4.1. Inputs required in order to create PAF prototype*

Initially the important characteristics were defined as drying time, durability and adaptability. These were expanded to include dry to touch after a known time, within a range of peel strengths, and a two-component or thermally activated system, which is translucent, non-hazardous and made from a defined amount of renewable resources. These requirements are expanded and described below.
The prototype requirements could then be defined with the aid of the knowledge gained from screening of existing casting technologies and reviewing that which is currently possible. The existing technologies examined included the following: epoxy resins, screeds, resin concrete, resin mortar, floor paint, vinyl and carpet tile. The application systems that are frequently used are brush, grooved trowel, roller, spray (pump and aerosol), bucket and shovel.

A search was conducted in order to investigate the current fluid systems based on renewable resources. This showed that there is little information currently available on such systems. The results of the search can be found in the 18-month report attached as Volume 2 of this portfolio (Carter, 2005).

The concept description set the amount of renewable materials contained in the product to be at 100 %. The literature search revealed no liquid biopolymer systems on the market that are 100 % renewable. There are some systems currently being investigated for use in the laminates industry based on vegetable oils (Fowler, 2005). However, these are not commercially available and contain a number of hazardous processes such as ozonisation and the use of volatile gases.

No patents were discovered in the course of this investigation that precluded further development work. Technologies in this area are still developing. Although there are many fluid-flooring systems, these are frequently industrial systems based on epoxy resins, concrete or paints, based on non-renewable materials and involve complex application methods. These are described in the next section and compared to the ideal characteristics of the PAF concept.

4.3.2 Current Marketplace Technology

Initial screening of flooring within the marketplace revealed a varied and extensive group of candidates. These included concrete, paints, vinyl and screeds. This section describes a consideration of these candidates to assess if they fulfil all of the PAF concept requirements. Therefore the screening of current marketplace technology also aided the definition of the PAF prototype requirements. The flooring types were then compared again against those requirements and it was noted that some of these candidates could fulfil some of the PAF prototype requirements. Those candidates described below are all industrial systems used in various applications.
Concrex is a tough epoxy resin mortar for repairing concrete floors. Floor paint is used decoratively, although hardwearing and is applied over another flooring, such as concrete. Epoxy gloss paint is generally solvent based and must be applied in well-ventilated areas. Flow Top is a slip-resistant coating, which can be overcoated. It is suitable for use on uneven and damaged concrete to produce a smooth, high strength surface (Watco, 2005).

Vinyl and linoleum were described in Chapter 2. They are flexible floor coverings provided in roll or tile form that are glued to the sub-floor. They are hard wearing and offer good flammability resistance. Whilst the basis of vinyl is PVC, the main basis of linoleum is linseed oil.

These candidates are compared to the PAF concept requirements that were identified in section 4.2 as it:

- Is a one or two part system
- Is made entirely from renewable resources
- Can incorporate other material as a sub-floor to provide designs that will be possible for the home-user to use
- Is simple to install- including setting and hardening quickly
- Offers an impervious barrier to liquids and micro organisms found in everyday use
- Is easy to clean
- Is versatile enough to be used in many climates.
- Is entirely biodegradable

<table>
<thead>
<tr>
<th></th>
<th>Concrex</th>
<th>Floor Paint</th>
<th>Epoxy Gloss Paint</th>
<th>Flow Top</th>
<th>Vinyl</th>
<th>Linoleum</th>
</tr>
</thead>
<tbody>
<tr>
<td>One or two parts</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>×</td>
<td>×</td>
</tr>
<tr>
<td>Renewable</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>✓</td>
</tr>
<tr>
<td>Incorporation of other material</td>
<td>×</td>
<td>✓</td>
<td>×</td>
<td>✓</td>
<td>×</td>
<td>✓</td>
</tr>
<tr>
<td>Simple to install</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>✓</td>
</tr>
<tr>
<td>Impervious</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Easy to clean</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Versatile</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Biodegradable</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>×</td>
</tr>
</tbody>
</table>

Table 4.1. Examination of existing technologies compared to PAF concept requirements
From the above table, patent search and discussions with those involved in the flooring industry, it was obvious that there were no flooring products currently available that would fulfil the PAF concept. The renewable content and biodegradability of the system proved to be the most challenging requirements to fulfil.

The system that was suggested for PAF, which will be described in section 4.4.2, did not have a 100 wt% renewable content. Based on this initial investigation, combined with the lack of fluid biopolymer patents, the renewable content of the prototype was set at 50 wt%. Therefore the prototype requirements were a compromise between the ideal and achievable situation.

By screening the existing technologies the range of required peel strengths could be defined. The maximum was defined as that of a strong adhesive on prepared concrete- approximately 10 MPa, and the minimum defined as that of a magnetic tile on a prepared screed- approximately 0.75 MPa (Mantle, 2004).

Based on this search, the prototype requirements were refined and described as:

- Dry to touch at 25°C after 6 hours
- 0.75 MPa < Peel strength on concrete (brushed and set) < 10 MPa
- Either
  - thermally activated system or
  - optically activated system or
  - several component system with at least one component liquid at 25°C
- Materials are non-hazardous (in laying/use/removal)
- Translucent enough to see clearly the sub floor through a 1cm layer
- Made from at least 50 wt% renewable materials with no more than 50 wt% non-hazardous materials making up the rest of the system

The next step was to compare those products in the market place that have already been identified to the prototype requirements.
Table 4.2. Examination of existing technologies compared to PAF prototype requirements

It can be seen from table 4.2 that the flooring systems selected do not fulfil the PAF prototype requirements. There are some that can be made from an increased renewable content, but have not reached the mass market. Therefore an alternative has to be sought.

4.4 Investigation of Candidate System

4.4.1 Introduction

It was clear that there was no immediate solution to the prototype requirements within the flooring industry or the biopolymer industry. A biopolymer may be defined as a polymer that is based on renewable resources. Biopolymers are still being investigated and are developing but have been used for a number of years.

Since the 1990s polymers based on renewable feedstocks and natural fibres have been used in a variety of applications, such as biodegradable capsules for drug delivery systems (PURAC, 2004), non-woven material in the replacement of human tissue (Eagles et al, 1997), waste bags and packaging material (Van de Velde, 2002). Biopolymers are also used in adhesives, fibres, animal products, personal care, medical, garden and more commonly packaging applications (Biopolymer.net, 2005).

Commercial biopolymers have found use in a wide variety of applications such as polylactic acid (PLA) used as face yarn in carpet tiles (Interface PLA, 2003), EverCorn Resin™ used in drinks containers (Japan Cornstarch, 2005) and another starch based polymer, Materbi™, used as packaging for Sainsbury’s supermarket chain’s apples and potatoes (Novamont, 2007).
More recently biopolymers have arisen due to a number of extraction processes and chemical pathways becoming available such as the cross-linking of epoxidised natural oils (Boquillon and Frigant, 2000). Starch-based polymers have been extensively investigated (Patel, 2003, Johnson, 2002, Van de Velde, 2002) and their properties are well documented. However, their mechanical performance does not generally reach the level of their petrochemical counterparts and therefore they cannot be used at the same level in applications. PLA, for example, has been used as an alternative to nylon in the carpet industry, although it does not provide the long-term aesthetic properties of its nylon cousin and flattens readily (Colton, 2004). Consequently nylon will continue to be used until PLA can be modified such that it performs as well in heavy contract situations. InterfaceFLOR is continuing this investigation using collaborative partnerships.

It was clear that external collaboration was vital to the success of this concept in order to provide material and expertise in chemical formulation. A collaborative partnership was initiated in conjunction with A and F to satisfy this need. They are leading biopolymer researchers and experts in crop processing. The ELO-based resin material that was suggested for the PAF concept is described in the next section.

### 4.4.2 Candidate Material

The material chosen was based on epoxidised linseed oil (ELO). It is manufactured from linseed oil that is produced from the flax plant, which yields oil and linen. Around 1 million tonnes of oil is produced annually, with 60,000 tonnes used in the EU of which 15,000 tonnes are used in the technical and chemical industries (Spencer, 2002). The oil has been used as a paint binder, wood finisher and in the production of linoleum which was described in Chapter 2.

ELO can be formed from the linseed oil during commercial processes. This process is described further in the next chapter. The next chapter also discusses a life cycle analysis that compares ELO with petrochemical alternatives, used as varnishes. These analyses show that ELO can compare favourably to a petrochemical alternative as a varnish. However, a more detailed analysis would be required in order to confirm this for a particular flooring product, once the attributes of this product are known. ELO will be considered for the next part of this analysis.

The fatty acid composition of linseed oil is dominated by C18 fatty acids, C18:2 (16 % of oil) C18:3 (50% of oil) (Turner, 1987). The main fatty acid, linolenic acid (C18:3) contains three carbon-carbon double bonds (Boquillon and Frigant, 2000). These are the bonds that are oxidised in the production of linoleum.
An epoxide is a cyclic ether with three ring atoms. The ring is an approximately equilateral triangle with highly strained bonds at 60° to each other. The strained ring makes epoxides highly reactive and susceptible to nucleophilic addition via the use of an acid or base. The ELO is composed mainly of epoxidised linolenic acid. The chemical structure of an epoxidised triglyceride of linseed oil is shown in Figure 4.2 (Overeem et al. 1998).

![Figure 4.2. Schematic diagram of ELO](image)

The ELO is a long-chained acid and a cross-linker is required to bind with the liquid ELO to produce a solid polymeric material. This could potentially be achieved at room temperature for the PAF concept.

A number of cross-linkers that can work with ELO to create a polymer have been described in the literature (Boquillon and Frigant, 2000). These are heated at 150°C for 20 minutes to facilitate cure, thus making them impractical for use with PAF. A selection of the cross-linkers described is indicated in table 4.3.
<table>
<thead>
<tr>
<th>Name</th>
<th>Formula</th>
<th>Molecular weight (g/mol)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phthalic anhydride (PA)</td>
<td><img src="attachment" alt="formula" /></td>
<td>148</td>
</tr>
<tr>
<td>Cis-1,2,3,6-Tetrahydrophthalic anhydride (THPA)</td>
<td><img src="attachment" alt="formula" /></td>
<td>152</td>
</tr>
<tr>
<td>Methyl-tetrahydrophthalic anhydride (MTHPA)</td>
<td><img src="attachment" alt="formula" /></td>
<td>166</td>
</tr>
<tr>
<td>Methyl-hexahydrophthalic anhydride (MHHPA)</td>
<td><img src="attachment" alt="formula" /></td>
<td>168</td>
</tr>
<tr>
<td>Methyl-endomethylenetetrahydrophthalic anhydride (METH)</td>
<td><img src="attachment" alt="formula" /></td>
<td>178</td>
</tr>
</tbody>
</table>

Table 4.3. Cross-linkers that can react with ELO to form a cured biopolymer (Boquillon and Frigant, 2000)

A cross-linker was suggested by A and F that could potentially be used to cure ELO at room temperature. The di-acid cross-linker is formed by the heating of dipropylene glycol in the presence of maleic anhydride as shown schematically in figure 4.3.

![Figure 4.3. Schematic diagram of cross-linker](attachment)
The manufacture of the cross-linker is described more fully in the next chapter and Chapter 4 of the 30-month report, included as part of this portfolio. The cross-linker is currently produced on a laboratory-scale from non-renewable resources. There is no rationalisation for this and this was discussed in a private communication with Dr. Jeff Hardy of the University of York and the National Non-Food Crop Centre on 17th February 2005. It was decided that much of the structure of the cross-linker could potentially be replaced by renewable resources, further reducing the environmental impact of the system.

The epoxide groups on the ELO and the acid groups on the cross-linker can react to form a network, shown schematically below.

![Reaction schematic](image)

**Figure 4.4. Schematic showing reaction of ELO with cross-linker**

The prototype requirements had listed the properties required from a system. This system contained at least 50 wt% renewable material, was non-hazardous, contained two liquid components at room temperature and was translucent after manufacture. Therefore the focus of the initial investigation was to tackle the remaining requirement by assessing drying time of the ELO-based resin material at room temperature. The peel strength was also gauged using prototype materials.
4.4.3 Results from A and F Collaborative Investigation

It was decided that drying time was one of the most critical factors to be determined for the ELO-based resin material since it would have to be practicable in order to be commercially viable. The material was known to be a two component system, both liquid and translucent at 25 °C, with at least 50 wt% renewable and the other component non-hazardous. The material was also known to bind well to a substrate (it was difficult to pull apart the samples manufactured by hand).

During the course of this investigation a 6-speed elcometer drying time recorder was used to assess drying time. This has been used extensively in the paint industry to assess drying time of coatings. British Standard EN 29117 describes a drying test using plungers, on which the drying time recorder is based. However, since this equipment was not readily available, the drying time recorder is used as a guide at A and F.

The mixture was applied on a rectangular shaped glass plate of dimensions 70 mm x 20 mm x 0.5 mm. A needle with a ballpoint was placed on this glass sample carrier and pulled through the mixture at a rate of 12 mm/hour. As the coating cures, the trace left in the coating by the ball identifies each stage of the cure. Initially the coating levels off under gravity as the needle is pulled through the liquid sample. Once it begins to cure, a thin, dry film appears on the surface and so the ball leaves a trace. When the ball no longer leaves a trace the coating is fully cured (Elcometer, 2005).

With a molar ratio of cross-linker:ELO of 3:1, theoretically all the epoxide groups of the ELO can react with all the acid groups of the cross-linker. With a molar ratio of 1:1, in theory, all the acid groups of the cross-linker can react with just two epoxide groups of an ELO molecule, resulting in a more flexible polymer. A molar ratio of 5:1 was also chosen to give an excess of crosslinker. The results from the drying time recorder are shown in figure 4.5 below.
Figure 4.5. Results from drying time recorder at room temperature

Dynamic mechanical and thermal analysis (DMTA) involved using a Rheometrics RSA II solids analyser to acquire a value for glass transition temperature. Mechanical tests were performed on a Zwick Mini Hasy System at A and F. These mechanical tests are not conclusive as they were conducted only to give an indication of properties. It is recommended that these tests be repeated in a controlled environment in order to achieve consistent results. The results for the ELO-based resin material cured at room temperature and the results from material that was cured at elevated temperature are compared in table 4.4 below.

<table>
<thead>
<tr>
<th>Ratio ELO: Crosslinker</th>
<th>Curing Temp (°C)</th>
<th>Curing Time</th>
<th>Stress-max (N/mm²)</th>
<th>Strain at Fracture (%)</th>
<th>Glass Transition Temp (°C)</th>
<th>Young's Modulus (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1:5</td>
<td>22</td>
<td>3 days</td>
<td>0.5</td>
<td>40.6</td>
<td>-4.4</td>
<td>2</td>
</tr>
<tr>
<td>1:3</td>
<td>22</td>
<td>3 days</td>
<td>0.4</td>
<td>32.3</td>
<td>-9</td>
<td>0.8</td>
</tr>
<tr>
<td>1:5</td>
<td>150</td>
<td>30 min</td>
<td>1.4</td>
<td>51.7</td>
<td>6.2</td>
<td>3</td>
</tr>
<tr>
<td>1:3</td>
<td>150</td>
<td>30 min</td>
<td>3.5</td>
<td>63.1</td>
<td>14.7</td>
<td>6</td>
</tr>
</tbody>
</table>

Table 4.4. Results of mechanical tests on material
The mechanical properties were tested three days after the reaction had begun to occur at room temperature. It may be that the reaction is still occurring, albeit very slowly. Therefore these tests should be repeated several times after reaction begins. It is recommended that they are repeated several days, weeks and months after the two components are mixed. The time that the materials should be left to allow resilient processes to cease will be expanded upon when the next stage of the project is defined further.

As previously stated, these tests were designed to give an indication of mechanical properties and can therefore be used as a guide to performance. The conclusion that can be reached is that these polymers are rubber-like in their performance, with low Young’s Modulus and high strain at failure. This is advantageous at this stage in the development of PAF as the material can resist impacts and properties can be further modified at a later stage.

The main drawback with the resin material is its curing time of over 50 hours. As a first step to reducing this, catalysts were introduced at 1 wt% in order to assess if a reduction in curing time could be achieved. The results of adding three catalysts to the molar ratio 1:3 are shown in figure 4.6.

1 wt% of catalyst would give a good initial indication of effect, although different amounts should also be investigated as part of the second stage of this project. Manganese is known as a surface dryer (Hardy, 2005), whereas tin and zinc are used in the form of salts in order to increase electron transfer during reaction. It may be that the manganese dries a thin coating quickly (as is shown by the drying time recorder), but does not work as effectively for thick coatings, which may be laid down as PAF (Hardy 2005).
Figure 4.6. Results of drying time with the addition of catalysts

These initial experiments showed that the curing time could be reduced by around 20 hours as a first attempt. Although this is dramatic, this requires further investigation, in order to verify the effect of changing the amount of catalyst, as there may be environmental factors that limit their use.

4.4.4 Discussion

The initial investigation into the PAF system proved promising, even though the drying time for the ELO-based resin material was still unacceptable. Some samples were manufactured in order to provide ‘proof-of-principle’ of the PAF concept. These are shown below.
Figure 4.7. Photograph showing PAF concept

Figure 4.8. Photograph showing PAF with inclusions
An important next step to develop the PAF concept is to consider the effects of different amount of catalysts on the reaction rate. There are also a number of other more powerful catalysts to consider, such as sulphuric acid and sodium hydroxide. These are not considered to be ‘environmentally friendly’ and are listed under the hazardous substances regulations (National Environment Agency, 2005). These may provide some indication as to how fast the reaction could occur at room temperature and effect on mechanical properties. If it is found that the curing time cannot be improved, even with these powerful catalysts, it is unlikely that the other catalysts will be able to improve it to the prototype properties required and some other system must be found.

The initial investigation has shown that, based on the materials tested, there is no immediate solution that fits the PAF concept. It has been shown that with this work the prototype requirements cannot be easily reached. Future work for PAF would have to be broken down into a number of further phases. The initial research and testing exercise, phase one and two, has been completed.

The resin material based on ELO has shown promise for the PAF system and a series of well-thought-out experiments will show if this system can fulfil the prototype requirements. The third stage of the investigation would take a further 12 months of project time (A and F, 2005). This would aim to increase the amount of renewable material, reduce curing time using renewable catalysts and develop concepts for application methods.

A SWOT analysis of this concept is summarised in table 4.5.
<table>
<thead>
<tr>
<th><strong>Strengths</strong></th>
<th><strong>Weaknesses</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Potentially sustainable as based on</td>
<td>Knowledge of material in-house</td>
</tr>
<tr>
<td>renewable resources</td>
<td>requires development</td>
</tr>
<tr>
<td>Demonstrates innovative R and D within</td>
<td>Costly</td>
</tr>
<tr>
<td>InterfaceFLOR, helping cement the</td>
<td>Delayed financial payback</td>
</tr>
<tr>
<td>position as market leaders</td>
<td></td>
</tr>
<tr>
<td>Patentable</td>
<td></td>
</tr>
<tr>
<td>Large customer reach</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>Opportunities</strong></th>
<th><strong>Threats</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Reassert InterfaceFLOR’s position as</td>
<td>Length of investigation high</td>
</tr>
<tr>
<td>number one in sustainability with</td>
<td></td>
</tr>
<tr>
<td>renewable material</td>
<td>Costs potentially high with no</td>
</tr>
<tr>
<td>Increases external partnerships</td>
<td>immediate payback</td>
</tr>
<tr>
<td>Leading the way for biopolymers to</td>
<td>External input required</td>
</tr>
<tr>
<td>enter mainstream</td>
<td></td>
</tr>
<tr>
<td>Possible increased collaboration with</td>
<td></td>
</tr>
<tr>
<td>InterfaceFLOR, US</td>
<td></td>
</tr>
</tbody>
</table>

*Table 4.5. SWOT analysis of the PAF concept within InterfaceFLOR*

PAF has the potential to be an innovative and sustainable system that offers unique design opportunities and brings the sustainability message to a wider audience. However, there may not be a solution to the requirements of the concept brief within the foreseeable future.

It can be seen that there is a great deal of work to complete in order to take PAF to stage three. There are a number of other stages that would follow to get PAF to prototyping stage. It may be that some additional work would take the ELO-based resin material towards the ultimate aim of PAF, whilst offering some intermediate goals. These are described in the next section.
4.5 Future Work

4.5.1 Introduction

There are a number of ways that this ELO-based resin material could be used at InterfaceFLOR, two of which are described in this section. The material could be investigated further by using these two concepts, thus increasing the knowledge of this system and bringing the PAF concept closer to completion.

4.5.2 Interlock

Interlock is a PVC tile system that was described in section 2.2.2.3. A subcontractor manufactures Interlock for InterfaceFLOR, Europe. It is produced using an extrusion process, relying on a heating and cooling cycle for the PVC to form the shape required. This is achieved using a heated extruder and mould.

The specifications state that Interlock should be manufactured from post-industrial waste, thereby reducing environmental impacts over the life cycle of the product. There has been a lack of consistency with the quality and quantity of feedstock and virgin material has to be used for the majority of production.

There are a number of concerns regarding the manufacture of PVC that are still being addressed such as the use of plasticisers, chlorine, dioxin and furan production (Carrol Jr et al, 2000). The chemicals produced as by-products in the production of PVC have been linked to increased likelihood of certain cancers, including testicular (Ohlson, 2000). It is obvious that PVC has a number of environmental concerns associated with its manufacture. It would therefore be preferable to offer the same qualities that Interlock currently offers with some alternative material.

The PAF investigation has been focused on reducing the curing time of the system at room temperature, although this can be reduced to 30 minutes at 150 °C. Since the PVC used to produce Interlock is currently extruded at elevated temperature and pressure, there may be reductions in energy requirements during manufacture.

This ELO-based resin would replace PVC by offering a similar service, at reduced environmental cost. ‘Sustainable’ Interlock is therefore described in the same manner as Interlock- hardwearing, anti-slip, practical and durable flooring. It is suitable for light to heavy use, such as can be found in an industrial setting. It is also flexible enough to be used for exhibition stands, retail and hospitality as it can be installed with an adhesive or laid loose.

A SWOT analysis of ‘Sustainable’ Interlock is summarised in table 4.6.
### Strengths
- More sustainable than PVC
- Can use established manufacturing techniques
- Demonstrates innovative R and D within InterfaceFLOR, helping cement them as market leaders
- Patentable
- Similar investigations in the US but can be continued within the UK
- Medium customer reach
- Transport costs reduced since a low density product is sought

### Weaknesses
- Knowledge of material in-house requires development
- Market requirements potentially low
- Investment in manufacturing equipment is required

### Opportunities
- Reassert InterfaceFLOR’s position as number one in sustainability with renewable materials
- Raise InterfaceFLOR’s profile in Green Chemistry Network
- Novel designs can be produced quickly

### Threats
- Length of investigation relatively high
- Other Interlock-style material already available commercially

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**Table 4.6. SWOT analysis of renewable Interlock concept**

Primarily this concept is a hardwearing, practical flooring. However, the add-on benefit is that it is designed to be environmentally preferable to the original Interlock. There is another area within InterfaceFLOR that this material could provide an environmentally preferable alternative to a current product, which is described below.
4.5.3 Backing System

There are a number of systems available for backing carpet before cutting into carpet tiles, two of which are used at Shelf Mills. They are known as Graphlex and Glasbac. The Graphlex backing has been described in Chapter 3, as the introduction of recycled filler was investigated for this system. The Glasbac system was described in section 2.2.3.2.1.

The Glasbac system is a thermoplastic composite that incorporates fibreglass for dimensional stability. However the primary backing constituent is based on plasticized and filled PVC. It is applied cool and heated to cure.

![Illustration of Glasbac backing system](image)

Figure 4.10. Illustration of Glasbac backing system (Interface Backing Systems, 2003)

PVC is manufactured from vinyl chloride (CH₂=CHCl), although it can be heavily plasticized, additives such as flame-retardants, stabilisers, pigments and fillers are usually added. It is a thermoplastic and therefore can be heated and cooled to form different shapes. Heat is required in this instance to cure the PVC due to the additives included.

PVC is a relatively expensive polymer in comparison to other constituents in the backing mix and therefore must be filled with more cost effective materials. It is mixed with plasticizers, resins and fillers in order to bulk the mix. The plasticizers and resins allow more filler to be added. At InterfaceFLOR the filler used is graded virgin limestone.
Although the Glasbac system has strict requirements, depending on the specifications required for the product, there is scope for varying the processing requirements. For example, the temperature of the heated rolls, cooling rolls and infrared heater can be varied. Altering the line speed can also vary the time taken to heat the material.

The PVC is applied cool and this temperature cannot be altered without some investment in capital costs. Therefore a liquid system is preferable for straightforward replacement. The system can then be heated and cooled in a number of ways without excessive modifications to the current processing equipment. A SWOT analysis is shown in table 4.7.

<table>
<thead>
<tr>
<th>Strengths</th>
<th>Weaknesses</th>
</tr>
</thead>
<tbody>
<tr>
<td>More sustainable than PVC used in current product</td>
<td>Knowledge of material in-house requires development</td>
</tr>
<tr>
<td>Can use established manufacturing techniques</td>
<td>Investment in current manufacturing equipment required</td>
</tr>
<tr>
<td>Demonstrates innovative R and D within InterfaceFLOR, helping cement them as market leaders</td>
<td>Absolute confidence in product required to change entire product range</td>
</tr>
<tr>
<td>Patentable</td>
<td></td>
</tr>
<tr>
<td>Could replace all carpet-tile backing in US although investigation can be continued within the UK</td>
<td></td>
</tr>
<tr>
<td>Instant customer reach to present customers</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Opportunities</th>
<th>Threats</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reassert InterfaceFLOR’s position as number one in sustainability with renewable material</td>
<td>Length of investigation relatively high</td>
</tr>
<tr>
<td>Raise Interface’s profile in Green Chemistry Network</td>
<td>Threat of copying high</td>
</tr>
<tr>
<td>Novel designs can be produced quickly</td>
<td></td>
</tr>
</tbody>
</table>

Table 4.7. SWOT analysis of PVC backing replacement
It can be concluded that the PVC application system may be modified such that a different material can be used. However, this material would need to offer similar properties to PVC both in processing and use. These would be processing times, residence times, viscosity at application and cost.

4.6 Conclusion

This chapter has introduced the PAF concept as a novel and innovative concept that is worthy of consideration. This concept would fit with InterfaceFLOR’s requirement to lead the flooring market through innovation. The PAF concept would also complement a future portfolio of flooring products that could be sustainable and be compatible with ‘Mission Zero’. However, it has also been noted that the solution to this concept is potentially available only in the distant future.

An investigation into the principle ELO-based resin material showed that the long drying time of the system at room temperature is the primary drawback. It was also seen that an attempt at reducing drying time through the addition of catalysts was successful. However, some of the catalysts used would not be compatible with the need to have sustainable materials. It is possible that other renewable catalysts are available that would perform in a similar way to those already tested. This would require further investigation. Other alternatives were then considered for this system.

It has been shown that other options for use of the ELO-based resin material within InterfaceFLOR are more viable than the PAF concept. These two concepts, renewable Interlock and backing system replacement, are worthy of consideration and therefore the ELO-based resin is worthy of further research. The investigation of the properties of this system is continued in the next chapter.
Chapter 5 Biopolymer System

5.1 Introduction

InterfaceFLOR has declared that it will become a company that will eliminate any negative impact it has on the environment by the year 2020. There are a number of ways that this could be achieved, although it has become obvious through the course of this project that revolutionary concepts and innovative materials are required. One such material was the biopolymer system described in the previous chapter.

This chapter describes the manufacturing route for the epoxidised linseed oil (ELO) and cross-linker, in order that the material can be more fully understood. This description also includes a brief analysis of the potential reduction in environmental impacts to be had by the use of ELO in comparison to a petrochemical alternative.

It was shown that the biopolymer system that has been described may be used at InterfaceFLOR in other capacities. This chapter describes an investigation into this material in order to gain more knowledge of its properties and potential uses. The manufacture of the samples is first described and then the mechanical tests undertaken. This investigation takes the form of changing processing conditions on a laboratory scale and measuring the effect on mechanical properties of the biopolymer.

Since one of the options for this biopolymer is to be used as a flooring product, these tests could be used as an indicative test of performance under flooring conditions. Once the properties are known, the best and worst samples could be taken forward for flooring tests and compared to a standard.

5.2 Material and Methods

5.2.1 Epoxidised Linseed Oil

Linseed oil is derived from the seed of the flax plant, with the fibres of the plant also being used in a variety of ways. Parts of the plant are used to make fabric, paper, rope, dye, varnish, medicines and soap. The flax plant is self-pollinating and takes around 100 days to mature (Flax Council, 2005). An example of the whole plant is shown in figure 1 below.
The raw oil is extracted from the seed of the plant via hydraulic pressure and is pale in colour (Encyclopedia.com, 2005). It is then chemically epoxidised to form the ELO, with the result of several reactive epoxy rings. The ELO is shown schematically in figure 2.

The epoxidisation process has environmental dis-benefits which will be briefly considered here. Dr Achim Diehlmann has conducted a life cycle approach analysis of this product in order to compare with petrochemical alternatives that are used as varnishes. This analysis included the consideration of fertilisers during the crop-growing phase and national transport.

Figure 3 below shows the cumulative energy expenditure (CEE), in GJ per tonne of ELO during the manufacturing phase. The comparison between centralised processing and a scenario where processing is more scattered, is shown. Figure 4 also shows the comparative CO$_2$ equivalent emissions for each phase of the process. Figures 5 and 6 show the overall comparison of energy and CO$_2$ impacts with the petrochemical alternative.
Figure 3. Life cycle analysis results for ELO showing energy consumed during manufacturing phase (Diehlmann et al, 2000)

Figure 4. Life cycle analysis results for ELO showing CO2 equivalent expended during manufacturing phase (Diehlmann et al, 2000)
These analyses show that ELO can compare favourably to a petrochemical alternative as a varnish. However, a more detailed analysis would be required in order to confirm this for a particular flooring product, once the attributes of this product are known. ELO will be considered for the next part of this analysis.
ELO is available commercially from a number of outlets and was obtained as Lankroflex L from PolyOne Polymer Coating Systems for this investigation.

### 5.2.2 Cross-linker

The cross-linking of the ELO is achieved by the use of a liquid di-acid to form a flexible polymer network. In order to function, the cross-linker must have at least two reactive groups, normally at opposite ends of the functional unit. If there were a single reactive group, the polymerisation would not be able to proliferate and long chains would not form. In the case of the cross-linker chosen, these reactive groups are acid groups that react with the epoxy groups on the ELO chain.

The cross-linker has been chosen as it was suggested by A and F as one that would likely react at room temperature, one of the requirements for the PAF concept. There are other cross-linkers that are available and have been described in the literature (section 4.2). These may also be worthy of further investigation when considering a system that cures at elevated temperature. This could be considered as part of the further work for this concept, which would require the input of a chemical specialist.

This cross-linker is not commercially available and must be produced on a laboratory scale, which is briefly described here. Heating a di-ether in the presence of maleic anhydride will produce the di-acid, shown schematically in figure 7.

![Figure 7. Di-acid formed by heating di-ether in the presence of maleic anhydride](image)

The di-ether used is dipropylene glycol which is a clear, odourless liquid at room temperature with a boiling point of 229-232 °C (Fisher, 2007). Maleic anhydride is a white, pungent solid with a tendency to sublime at room temperature. It is most commonly produced in the form of white flakes or blocks that melt at 52-55 °C (Fisher, 2007).

The constituents are mixed and held in a sealed, round-bottom flask with a nitrogen atmosphere. They are then heated to around 95 °C (± 5 °C) and held at this temperature for around 3 hours. This has been determined by A and F as it is effective for full reaction. The photograph below shows the mixture as the reaction occurs.
Figure 8. Di-acid being produced on a laboratory scale

The cross-linker is then produced as a liquid and can be stored until required. The samples are produced by mixing the cross-linker with the ELO and this is described in the next section.

5.3 Method of Sample Manufacture

In order to produce solid samples of known size for the mechanical tests, the two liquid components needed to be mixed together to form a specific volume of material. This would usually require around 500 ml of liquid to produce sufficient samples for the screening programme of tests.

The ELO and cross-linker were mixed thoroughly using a magnetic stirrer at 3000 rpm for 2 minutes. This speed and time were chosen as it has previously been shown to provide an effective mix (Koelewijn, 2005). This speed and time were also used in further trial experiments in which a vegetable dye was added and visual inspection suggested that the dye was distributed evenly after 2 minutes of stirring.

Previous experiments had shown that the system would be cured fully after a cure cycle of 150°C for 30 minutes (Koelewijn, 2005, Boquillon and Fringant, 2000). The mould to be used was pre-heated in an oven to 5°C above the desired temperature. The elevated temperature was required as there is a temperature fall when the oven door is opened. The mould was removed, the liquid poured into the mould and then replaced in the oven. However, immediately upon returning the mould to the oven, the temperature was reset to the desired value with a variance of ±1 °C, in line with typical processing controls on an industrial scale.
After the required amount of time, the mould was removed from the oven and the sample was removed. It is placed on a wire rack in order to allow full air circulation at room temperature.

There are no British Standards that describe the post-cure conditioning required for this particular system. However, there are examples within the standards for other plastics and these are used here. Plastics that have undergone cure often need to come to equilibrium, which is achieved through conditioning. In the present study samples were left at room temperature for 72 hours. This ensured that any resilient processes have completed in accordance with BS EN ISO 1798:1999.

For each set of samples, at least six specimens were produced- this is to ensure that there were at least five samples that are suitable for testing, as specified in BS 2846-2:1981 ISO 2602-1980.

Batches of samples were manufactured with a view to assessing the process variables indicated below

- Molar ratio of components when cured at 150 °C for 30 minutes
- Cure times at a molar ratio of 2.5:1 (Cross-linker: ELO) when cured at 180 °C
- Cure temperatures at a 2.5:1 molar ratio (Cross-linker: ELO) when cured for 30 minutes

The 2.5:1 molar ratio was kept constant during the cure time and temperature parametric studies since simple stoichiometric considerations suggested that this ratio should give near-full cross-linking, although complete cross-linking would not be expected in practice because the mix hardens as cross-linking progresses and the mobility of the molecules decreases rapidly.

180°C is the temperature at which carpet backing systems are processed currently in order to cure the PVC applied. Therefore this temperature was used for comparison purposes and to assess the feasibility of substitution.
5.4 Tensile Test

5.4.1 Test Method

Tensile tests are often used in the materials industry to give an indication of properties in service. During use, materials may be subjected to a number of loading regimes, e.g. short and long term, including fatigue and creep and dynamic impacts. These will affect the ability of that material to withstand further loading. Tensile tests are designed to replicate some of the extreme conditions and therefore give an indication of what will occur in practice. These individual tests do not require a large amount of material, although it is important that a number of tests are conducted to verify significance.

Tensile tests were used in this investigation in order to facilitate greater understanding of the biopolymer. It could be that these tests could be used as an indicator of the performance of the system as flooring. The suggestion correlation will be investigated in Chapter 6.

The larger sample that had been removed from the oven was then cut using a hand press and cutter specified by BS EN ISO 1798. The material was cut into a dumbbell shape (see figure 9). This shape was used to provide a region of well-defined gauge length, in which the stress can remain constant during testing, and to reduce the likelihood of premature fracture at the grips of the machine.

![Figure 9. Dumbell used in tensile test](image)

The cut samples were conditioned for 24 hours to ensure that the atmospheric effects were the same with each test. A controlled atmosphere is used for traditional flooring tests of 65 ± 5 % RH and 20 ± 1 °C. It therefore seemed prudent to use this conditioning for the samples in each case, as well as testing in this environment.

After conditioning and cleaning off any loose particles, the central portion of the dumbbell was measured across the width and thickness to ± 0.1 mm. Three measurements were taken and the arithmetic mean value for the width and thickness calculated. Five samples were measured in turn and the results logged.
The gauge length was marked on the samples, approximately equidistant from the mid-point, not more than 50 mm ±1mm apart (EN ISO 1798:1999).

The test specimens were then clamped in the Testometric Micro 350 calibrated by UKAS to ISO 5893 and BS EN ISO 7500-1:1999 to grade 0.5, taking care to align the longitudinal axis of the test specimen with the axis of the testing machine and to set the gauge length correctly. The samples were tested in accordance with BS EN ISO 527-1:1996 BS 2782-3: Method 321:1994 ISO 527-1:1993 in order to determine the tensile behaviour of the test specimens. The stiffness of the machine has been calculated by the manufacturers and is accounted for in the electronic calculation of the distance moved by the crosshead.

The test specimens were extended along its major longitudinal axis at a constant speed of 100 mm/min until fracture. Any fractures that occurred outside the gauge length, within 10 mm of the jaws or which were associated with an obvious defect were discarded.

The maximum force and elongation was measured electronically using the Testometric Micro 350 and a stress-strain graph could be derived, similar to the schematic in figure 10.

![Schematic stress-strain curve](image)

**Figure 10. Schematic stress-strain curve**
From the graphs, the properties of $\sigma_y$ (yield stress) and $\varepsilon_{\text{max}}$ (maximum strain) were then determined. The Young’s modulus of elasticity was calculated from the stress at a strain of 0.0005 and the stress at a strain of 0.0025 (i.e. a secant modulus between 0.05 and 0.25% strain in accordance with BS EN ISO 527-1:1996).

These calculations were completed for each of the samples and the arithmetic mean and standard deviation were found.

### 5.4.2 Results

The results from the tensile tests are shown in figures. 11 - 13. Figure 11 shows the effect of varying molar ratio at constant cure time and temperature, figure 12 shows the effect of varying time at a constant molar ratio and cure temperature and figure 13 shows the effect of varying cure temperature at a constant molar ratio and cure time. The data points represent the average of at least five tensile tests and the extent of the error bars indicate plus and minus one standard deviation. The solid lines highlight the trends of the data.

![Graph showing mechanical properties](image)

*Figure 11. Mechanical properties measured as a result of tensile tests on material cured at 150 °C for 30 minutes*
Figure 12. Mechanical properties measured as a result of tensile tests on material with a 2.5:1 molar ratio (diacid:ELO) cured at 180 °C.

Figure 13. Mechanical properties measured as a result of tensile tests on material with a 2.5:1 molar ratio (diacid:ELO) cured for 30 minutes.
5.4.3 Discussion

5.4.3.1 Altering Molar Ratio

It is clear from the graphs in the previous section that varying the process parameters has a significant effect on the properties investigated (Young's Modulus, strain to failure and peak stress).

With regard to molar ratio, theoretically at a molar ratio of 2.5:1 all the reactive groups have combined to create the strongest polymer. If there are a larger number of cross-links, there will be a larger amount of force required to break these links and destroy the polymer, therefore the polymer will be stronger. However, it can be seen that the nominal peak stress tends to increase and then decrease with a peak at a ratio of diacid: ELO of approximately 2:1. There is a similar trend observed for the Young's Modulus with a peak occurring at a ratio of approximately 2:1 followed by a sharp fall.

This peak can be explained if the mobility of the components is considered. In order for the reactive groups to combine, they must first meet. As the reaction occurs, a more viscous polymer begins to form. Viscosity can be a visual indicator of the peak of reactivity. As the viscosity increases, the mobility of the components decreases and therefore there is less likelihood that the reactive groups will meet and combine further. This can also be affected by steric hindrance where reactions are physically blocked from reaching reaction sites by other parts of the structure. There comes a finite point beyond which the mobility of the reactants is restricted and no further reactions can occur, despite an increase in cross-linker added to the system. At higher molar ratios, there will be excess diacid in the system. It is suggested that this will then act as a plasticiser and fill the gaps left by the cross-linking process. This is shown by the decrease in Young's Modulus and peak stress beyond the 2:1 ratio.

The more diacid that there is available for cross-linking in the system, the greater the likelihood that an individual reaction will occur and therefore, the greater the amount of cross-linking there is that occurs. If there are more cross-links in one system than another, it will have a greater Young's Modulus and strength. This is because there is more force required to stretch and break the higher density of bonds.

5.4.3.2 Altering Cure Time

Figure 12 shows that at 180 °C increasing the cure time has a dramatic effect on Young's Modulus. There is a less obvious effect seen on the peak stress and strain to failure.
As described above, mobility and curing is an issue as the two components are mobile in the liquid form and must meet for the reactive groups to combine to form a solid polymer. These areas of solid polymer forming in the two liquid components cause the liquid to be more viscous and therefore the remainder of the reactive groups are less mobile as reaction time continues.

Visual observation suggested that the material was solid after 5 minutes conditioning at 180°C. Beyond these five minutes it is argued that the reactants are not sufficiently mobile to create any new cross-links between independent molecules. Heat is continuously added to the system as it is held at elevated temperature. This heat energy may be used by the system in other ways, such as increasing the number of cross-links with neighbouring molecules and therefore increasing the stiffness and strength of the system.

The peak stress continues to increase gradually with cure time, whereas strain to failure remains relatively stable. It is theorised that this is because the strain will not increase any further with additional cross-linking.

It has already been shown that the peak stress and Young’s Modulus at 150 °C for 30 minutes occurs at a 2:1 ratio. Therefore it is theorised that there is excess diacid in this system. With the heat energy input this excess diacid may react further with the ELO, although a lack of mobility may restrict these reactions.

There is a plateau in the Young’s Modulus and peak stress which occurs after 20 minutes. It may be that beyond this time there are no further reactions that can occur as neighbouring molecules have reacted as fully as they are able. Therefore the stiffness and strength will not increase further.

5.4.3.3 Altering Cure Temperature

Figure 13 shows the effect of altering cure temperature on mechanical properties. It can be seen from this graph that there is little change in peak stress with an increase in temperature. There is also little change in the strain to failure. However, Young’s Modulus falls slightly with an increase in temperature.

It was shown by the previous experiments that after 5 minutes at 180 °C the system had become solid. It is theorised that at these cure temperatures the systems would also have been cured at times much less than 30 minutes. The visual observation of the cure indicates that the reactants are no longer mobile and therefore cross-links between different molecules are unlikely. There may however, be further cross-linking between neighbouring molecules.
At greater temperatures, with excess diacid, it is theorised that there are a greater number of reactions that become available, as the activation energy required is surpassed. If a greater number of reactions are possible, then the material will become more viscous more quickly and mobility of constituents will be lost.

Since not all the reactive groups on the ELO have equal activation characteristics, there are then more reactive groups available at greater temperature. The diacid that was previously in excess at these ratios may then react with newly available ELO groups and therefore create linkages which are not network forming which results in a less stiff structure. This would explain the slight drop in Young’s Modulus, with little effect on the peak stress.

5.5 Conclusion

It has been shown that altering processing parameters of this system can be effective in changing material properties. Strain increases with increasing molar ratio, whereas the Young’s Modulus and peak stress peak at the 2:1 molar ratio (Cross-linker :ELO). It has also been shown that increasing cure time will have a dramatic effect on Young’s Modulus, but less so on peak stress and strain to failure. Altering the cure temperature during a 30 minute cure time has little effect on the mechanical properties.

It can be concluded that the resin cures sufficiently at elevated temperature in a much shorter time than the 30 minutes originally predicted. This may be of value when considering other processing routes for this system.

It is still debatable whether a greater Young’s Modulus, peak stress or strain to failure would be more beneficial for a flooring product. It is anticipated that a combination of both would be preferable. This would only be confirmed by testing the samples using traditional flooring tests. The ‘best’ and ‘worst’ samples are now selected for flooring tests and the results described in Chapter 6.

The next chapter describes the next stage of this investigation where samples are used in both flooring tests and flooring trials, i.e. they are placed as a flooring product in-situ. The results will show whether this resin is appropriate for use in any of the routes suggested for this biopolymer at InterfaceFLOR.
Chapter 6 Flooring Tests

6.1 Introduction

The previous chapter described the investigation of an ELO-based resin material that could potentially be used in a number of ways at InterfaceFLOR. This research focused on altering the processing conditions of the system and measuring the resulting change in mechanical properties. Although this investigation was useful for characterising the material and reducing the volume of material needed for each test, it did not directly determine the way in which this material would perform as a floor. This chapter aims to address this issue by comparing the results from mechanical testing with the performance of the ELO-based resin under flooring tests.

In order to determine the performance of this system as flooring, it must be tested using the standard industry methods. These standard tests were described in section 2.3, which require a full product to be made and a large volume of material (> 1 m²). Tensile tests were used to compare the ‘best’ and ‘worst’ samples from the previous investigation and a known sample of resilient PVC flooring, Interlock. In Chapter 4 the possibility of replacing the PVC in Interlock was considered and therefore it is prudent to compare the results for this ELO-based resin against the existing material. The test methods used to assess wear are described in section 6.3 and the results of these tests are shown in section 6.4.

The results from the investigation described in the previous chapter indicated that the ELO-based resin material was cured after 20 minutes at 180 °C. Since it is advantageous from both an economic and environmental perspective to have reduced time at temperature for processing, the samples were then cured at 150 °C for 20 minutes and the results compared to those from a 30 minute cure time. The results are described in section 6.5.

Filler is often added in large quantities to PVC in order to reduce cost and increase bulk. It was considered prudent to fill the ELO-based resin material in a similar manner and perform the same tests. Unfortunately it was not practical to perform tensile tests on the filled material since it contained large numbers of voids after manufacturing, but it was possible to carry out flooring tests to give an indication of performance to be expected in service. The results from the tests are described in section 6.6.
The wear exhibited by the flooring is normally assessed visually. It was suggested that some colour change will occur during in-situ testing, due to increased amounts of soil or wear. An accelerated wear regime was conducted on selected samples using a standard flooring test. The change in colour during this regime was evaluated and the results are described in section 6.7.

In order to be viable as a flooring material, the system must also be resistant to staining and accidental spillage of materials. Tests to assess the resistance to staining and a hot metal nut are described in sections 6.8 and 6.9.

6.2 Materials and Sample Preparation

The samples for the regime of flooring tests were manufactured in a similar way to those required for the investigation described in the previous chapter. In order to form samples of a known size, the two liquid components (ELO and cross-linker) were mixed together to form a specific volume of material. A typical batch size was in the order of 1 litre, in order to produce sufficient material for each flooring test. The samples to be produced were approximately 30 cm x 15 cm for each flooring test and formed in a rectangular mould. As some tests, such as the stain resistance and flammability test, required a smaller sample size, the larger samples were simply cut to size.

If required, filler was added at this stage and mixed thoroughly. The filler chosen is from the same source as described in Chapter 3. Addition of filler was problematic as it increased the viscosity of the system considerably at room temperature. It was found that by increasing the temperature of the two components separately before mixing, viscosity could be greatly decreased and therefore a larger amount of filler could be incorporated. However, all previous experiments did not include this pre-heating regime and the effects on the system were unknown. Since the effect of heating the individual components separately had not been investigated previously, this option was shelved. This is an avenue worthy of future consideration for future work.

The filler was added to the ELO and cross-linker at room temperature and a maximum saturation of approximately 50 wt% filler was achieved. The samples were tested with the addition of 25 wt% and 50 wt% filler. The 50 wt% filler was chosen since it was near the maximum saturation of filler that could be obtained at room temperature. The 25 wt% filler was chosen as an intermediate amount
The mixed liquid components were transferred to a non-stick rectangular-shaped metallic mould that was able to hold the specified volume of material. The mould to be used was pre-heated in an oven to 5°C above the required temperature. The elevated temperature was required to compensate for the temperature fall when the oven door is opened. The mould was removed, the liquid mix poured into the mould and then replaced in the oven, after which the temperature was reset to the required value with a variance of ±1 °C, in line with typical processing controls on an industrial scale.

It was found from the previous investigation that samples were fully cured after 20 minutes at elevated temperature. Therefore samples were manufactured that were cured for both 30 minutes and 20 minutes and compared, which is described in section 6.5. After the required cure time, the now-solid sample was removed from the mould and placed on a wire rack in order to cool at room temperature. This allowed full circulation of air around the sample.

There are no British Standards that describe the post-cure conditioning required for this particular system. However, in the previous study samples were left at room temperature for 72 hours, in accordance with BS EN ISO 1798:1999 and the same method was used for this investigation.

During the mixing regime, it was inevitable that air would be incorporated into the liquid sample. This could be minimised although not eliminated through careful mixing. The samples that did not include filler had a very low viscosity once the temperature had increased and therefore the air was able to escape from the mix. This was not the case with the filled samples that were considerably more viscous. Air could escape from the mix at the surface in contact with the air, but not at the surface in contact with the mould. This was observed from visual inspection of the sample. Therefore the two sides were assessed separately. The surface that was in contact with the air during the manufacturing phase is described as up (U) or face down (D).

Samples of Interlock were also used as comparison samples and were sourced from commercially available product.

The samples that were manufactured are described for each test, but are summarised as:

- 2:1 molar ratio, cured at 150 °C for 30 minutes
- 2:1 molar ratio, cured at 150 °C for 20 minutes
- 2:1 molar ratio, cured at 150 °C for 20 minutes with 25 wt% filler
- 2:1 molar ratio, cured at 150 °C for 20 minutes with 50 wt% filler
- 1:1 molar ratio, cured at 150 °C for 30 minutes
6.3 Test Methods

6.3.1 Tensile Tests Undertaken on Samples Used in Flooring Tests for Comparison Purposes

The previous chapter described the investigation of the ELO-based resin material using mechanical tests. Tensile tests are often used to give an indication of performance to be expected in practice. This investigation showed that there was some correlation between processing parameters and resulting mechanical properties.

The tensile tests that were used in this part of the investigation are the same as those described in the previous chapter. The dumbbell-shaped samples were cut from the 30cm x 15cm sample to provide at least 5 samples. Any remaining material could be used for flammability testing. The results from the tensile tests were compared to some flooring tests.

6.3.2 Flooring Test Methods Used for Comparison Purposes

The tests that are commonly used in the flooring industry were described in section 2.3. Those used most often at InterfaceFLOR and hence the tests that were used for the present investigation are:

- Static loading (BS 4939:1987, ISO 3416-1986): A modified version of this standard is used whereby a pressure of 700 kPa is applied to the sample via a steel foot of radius 10 mm for a time of 1 hour. The resulting loss of thickness is measured. The load is then reapplied for 23 hours before the loss of thickness is again measured.
- Vetterman drum (BS ISO 10361:2000): A steel ball with rubber feet revolves inside a drum, designed to fatigue the sample that is lining the inside of the drum
- Lisson-Tretrad (BS EN 1963:1998): A method of abrasion resistance measurement where a series of rubber feet are loading and slipped on the sample, similar to the scuffing that might be expected from dragging shoes
The static loading test results in a grading which relies on the expert judgement of experienced assessors through visual assessment, in addition to the depth change measured. The grading is divided into 5 “ratings” as are the other tests. A grading of 5 would mean that there were no remaining marks visible after the test had completed. A score of 3 or above indicates that the pass limit for heavy contract use has been achieved. A score of 1 would be very poor indicating that the sample had undergone a severe change during testing.

The Vetterman drum and Lisson Tretrad tests also result in a grading which relies on the expert judgment of experienced assessors through visual assessment. This grading is again divided into 5 “ratings”. 5 is the highest rating that can be given and indicates that the sample has performed very well and is visually unchanged as a result of the test. Again, a score of 3 or above would be the pass limit for heavy contract use for carpets.

The British Standards dictate that each wear test described above needs to be carried out on the samples only once and there will be deviation between test samples. Since the purpose of the tests is to assess samples against a known scale, similar results would be expected when repeating the tests with similar samples.

6.3.3 Use of Colour as an Indicator of Wear

When conducting flooring tests, as described above, visual assessment is normally used to assess changes in wear. Although this is a useful method, it was suggested that there may also be a change in colour of the samples with accumulation of wear. It was also suggested that measuring colour change may indicate accumulation of soil or further curing of samples with time. Measurement of colour change may be used in conjunction with visual assessment methods. In order to assess the change in colour of the samples, some method of measuring colour must first be established. Colour is considered to be a three-dimensional measurement, shown schematically below.
The centre L* axis shows L = 0 (black or total absorption) at the bottom. At the centre of this plane is neutral or grey. The a* axis runs from left to right. A colour movement in the +a direction depicts a shift toward red, one in the –a direction a shift towards green. Along the b* axis, +b movement represents a shift toward yellow and a –b movement towards blue. Therefore, a colour that has a negative a* value and a zero b* value, with a high L* value will appear as a very light green. A more in-depth description of colour measurement theory can be found in the 42-Month report, which forms part of this portfolio.

At InterfaceFLOR, A Chroma Meter CR-210 was available as it is used to measure colour changes of production samples from trials. This was used to assess the colour of the samples. The meter uses a xenon arc lamp that produces a diffuse and even illumination across the surface of the sample via the use of a mixing chamber. Only light reflected perpendicular to the sample is collected and analysed (Minolta, 1998). The equipment used is shown in the figure below.

*Figure 6.1. The L* value is represented on the centre axis. The a* and b* axes appear on the horizontal plane (X-Rite, 2004)*
A double-beam feedback mechanism measures both incident and reflected light through the use of six high-sensitivity silicon photocells.

The illumination is applied over a 50 mm diameter circular area with a 0° viewing angle. This wide diameter is particularly useful for measuring surfaces that contain a variety of colours since spot colour is then averaged. The results are then averaged and values for L*, a* and b* are calculated by the meter.

The total colour difference $\Delta E$ is also calculated using the L*, a* and b* colour coordinates. The difference between the original colour measured and the current colour measured is calculated for the three co-ordinates. $\Delta E$ is defined by the equation below.

$$\Delta E = \sqrt{(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2}$$

This calculation of $\Delta E$ gives one value for the difference in colour and this will be calculated for the trial described in section 6.7. A $\Delta E$ of greater than 1 is that which would be detected by the trained human eye (Colorspan, 2007).

Specular reflection can result from the use of this particular type of illumination although there are mechanisms in place to compensate for this (Minolta, 1998). Very glossy surfaces cannot be reliably measured using this system. The Chromo Meter is regularly calibrated using a calibration plate before use. It was seen visually that this calibration plate has an equally reflective surface as the glossiest sample. Therefore the effect of gloss may be discounted.
Since the colour is already averaged over the surface, it is not necessary to undertake a number of measurements for each sample. However, a scouting trial was conducted whereby the same sample was repeatedly measured using this method. This showed that there was high consistency with results.

In order to verify that these colour measurements were an effective way of measuring wear, an accelerated wear test was performed. This is described in section 6.7.

6.4 Comparison of Tensile Tests with Flooring Tests

6.4.1 Introduction

It is suggested that these tests could be used as a screening mechanism for future materials to be used as flooring products, since it is predicted that mechanical properties are related to performance in service, although this relationship is not yet fully understood. It is also proposed that the properties determined from a sample test may highlight differences in material characteristics relevant to flooring performance, without requiring a large volume of material to undergo testing.

The purpose of this part of the investigation is to assess whether the tensile tests suggested as a proxy for the flooring tests are a suitable substitute. Therefore the ‘best’ and ‘worst’ samples were identified from the previous investigation of mechanical properties and compared with a known product, PVC Interlock. The tensile test method used is the same as that described in section 5.4.

6.4.2 Tensile Test Results for Samples Used in Flooring Tests

The ‘best’ results determined from the previous investigation, were from a 2:1 molar ratio, cured at 150°C for 30 minutes (now termed sample A) which had a Young’s Modulus of approximately 6 MPa and a peak stress of just less than 2 MPa, although it did not have the highest strain to failure. The ‘worst’ results were from a 1:1 molar ratio, cured at 150°C for 30 minutes (now termed sample B) which had a low Young’s Modulus of under 3 MPa and peak stress of 0.5 MPa, with an associated low strain to failure of approximately 30 %.

The tensile results for samples A and B are plotted in figure 6.3, together with results for a sample C, which is a PVC Interlock tile. This sample was tested in the same manner as the other samples (section 5.4). In summary, the samples were:

- Sample A- 2:1 molar ratio, cured at 150°C for 30 minutes
- Sample B- 1:1 molar ratio, cured at 150°C for 30 minutes
- Sample C- A PVC tile that has been used as a stand-alone flooring product
Figure 6.3. Mechanical properties determined from tensile tests on samples also tested using traditional flooring tests

The tensile tests showed that Sample C, the PVC product, had a markedly higher Young’s Modulus, peak stress and peak strain than the other samples. Sample A had properties that were approximately twice those of sample B. Therefore it would be expected that sample C would outperform both the ELO system samples in the flooring tests. The next part of this investigation is to investigate whether this is the case. These tests are described in the next section.

6.4.3 Results of Flooring Tests for Samples Used in Tensile Tests

The results of the flooring tests on the samples used in the tensile tests are summarised in table 6.1. Here ‘structure’ and ‘shade’ are assessed separately. A change in structure would normally be indicated by a flattening of the carpet fibres. For these tests, it is the wearing away of surface material that is assessed. A change in shade is indicated by the sample becoming discoloured, either through soil or the wear of the surface allowing the core of the sample, which may be a different colour, to show through.

<table>
<thead>
<tr>
<th>Test Type</th>
<th>Measured Quality</th>
<th>A (2:1 molar ratio)</th>
<th>B (1:1 molar ratio)</th>
<th>C (PVC tile)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass</td>
<td>g/m²</td>
<td>10300</td>
<td>10000</td>
<td>7400</td>
</tr>
<tr>
<td>Thickness</td>
<td>mm</td>
<td>9.9</td>
<td>10</td>
<td>6.9</td>
</tr>
<tr>
<td>Static loading</td>
<td>Compression (mm)</td>
<td>0.2</td>
<td>0.5</td>
<td>0.4</td>
</tr>
<tr>
<td>----------------</td>
<td>-----------------</td>
<td>-----</td>
<td>-----</td>
<td>-----</td>
</tr>
<tr>
<td></td>
<td>Depth of marks after 1 hr (mm)</td>
<td>0</td>
<td>0</td>
<td>0.1</td>
</tr>
<tr>
<td></td>
<td>Visibility of marks (Grade)</td>
<td>5</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Vetterman Drum (5000 revolutions)</td>
<td>Structure</td>
<td>5</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>(Grade)</td>
<td>Shade</td>
<td>5</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>Overall change of appearance</td>
<td>5</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Vetterman Drum (22,000 revolutions)</td>
<td>Structure</td>
<td>4.5</td>
<td>3</td>
<td>5</td>
</tr>
<tr>
<td>(Grade)</td>
<td>Shade</td>
<td>4.5</td>
<td>3</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>Overall change of appearance</td>
<td>4.5</td>
<td>3</td>
<td>5</td>
</tr>
<tr>
<td>Lisson-Tretrad (400 cycles)</td>
<td>Structure</td>
<td>5</td>
<td>3.5</td>
<td>5</td>
</tr>
<tr>
<td>(Grade)</td>
<td>Shade</td>
<td>5</td>
<td>3</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>Overall change of appearance</td>
<td>5</td>
<td>3.5</td>
<td>5</td>
</tr>
</tbody>
</table>

*Table 6.1. Results of flooring tests*

### 6.4.4 Discussion

The static loading test results were performed on similarly-sized material. These show that sample A performed slightly better than C, which in turn was considerably better than sample B. However, all samples received a grade 5 based on their performance.

All of the samples performed particularly well in the Vetterman Drum test after 5,000 revolutions, achieving a grade 5. However, after a complete cycle of 22,000 revolutions sample B was significantly poorer than the other samples. Sample A and C remained comparable with only a slight variation in performance.

After 400 cycles on the Lisson-Tretrad test samples A and C both achieved a top grading. Again, sample B achieved a slightly poorer rating of 3.5. However, even this grading could be acceptable in certain applications.

The tests showed that sample A and C would have been passed at a heavy contract rating- suitable for any number of applications in practice. The results from the flooring tests shown in table 6.1 can be compared with the tensile test results shown in figure 6.3. The tests show the comparison between two ELO-based resin materials cured at 150 °C for 30 minutes with different molar ratios (2:1 and 1:1, samples A and B respectively) and the PVC tile- sample C.

It was clearly seen that sample C had a much higher Young’s Modulus, peak stress and strain to failure than the ELO-based resin samples. Sample A, the 2:1 molar ratio, also had appreciably higher properties than sample B, the 1:1 molar ratio.
It might therefore be predicted that sample C would perform significantly better in the flooring tests than the ELO-based resin material samples. However, it was seen that both sample A and C perform well, achieving a level 5 in a number of categories. Given that the mechanical properties were so dissimilar, with sample C performing exceptionally well, this result is surprising.

In the example of these particular tests it can be seen that sample A is fit for the purposes of these tests and would be passed as a level 4.5. Sample A is therefore adequate for the purposes of flooring. It is suggested that the performance of PVC in these tests far exceeds that required for the most demanding contract use since it achieved the highest grading in a number of tests.

The tensile tests have proved useful in identifying those samples that would perform better during the flooring tests. It is still debatable exactly which combination of Young’s Modulus, peak stress and strain to failure would be more beneficial for a flooring product. It is anticipated that a combination of all of these would be preferable and this has been validated by the preliminary flooring tests. The PVC flooring product was shown to have the highest results from the tensile tests and best results from the flooring tests. However, it may be that that the product has been over-specified for this use. Therefore the mechanical properties may also be above that required for a flooring.

The tensile tests from the previous chapter indicated that the samples would be cured at 20 minutes at 180 °C, less than the 30 minutes specified. If this were the case, then energy savings could ultimately be made as the sample would cure in less time at lower temperature. This was investigated and the results shown in the next section.

6.5 Effect of Reducing Cure Time on Mechanical Properties

6.5.1 Introduction

The samples that were identified as the ‘best’ and ‘worst’ ELO-based resin material samples were at the 2:1 and 1:1 molar ratio. The previous chapter also described the likelihood that the ELO-based resin material was cured at a lesser time of 20 minutes and that any amount of cure above this time would be detrimental to mechanical properties. If the ELO-based resin material could be fully cured in a lesser time, the process of cure could be less energy-intensive and hence offer reduced environmental impacts.
In order to confirm this, two samples were manufactured at these ratios and cured at 150 °C for 20 minutes. The samples were then subjected to tensile tests in the same manner as described before. The results are again compared to the PVC sample and described below.

6.5.2 Results

![Graph showing results of tensile tests on ELO-based resin material at a 2:1 and 1:1 molar ratio cured at 20 minutes and 30 minutes](image)

The graph above shows the results from the tensile tests on the ELO-based resin material. The standard deviation is again shown by the error bars. The samples are labelled where:

- Sample A is a 2:1 molar ratio, cured at 150 °C for 20 minutes
- Sample B is a 2:1 molar ratio, cured at 150 °C for 30 minutes
- Sample C is a 1:1 Molar ratio, cured at 150 °C for 20 minutes
- Sample D is a 1:1 Molar ratio, cured at 150 °C for 30 minutes
6.5.3 Discussion

The graph shows that the results that were cured for 20 minutes had higher Young's Modulus and peak stress than their counterparts cured for 30 minutes. These results indicate that adding heat beyond 20 minutes cure time may have a detrimental effect on the Young's Modulus and peak stress, which was shown by the samples tested in the previous experiments in chapter 5.

The associated strains to failure are also changed by the processing of the ELO-based resin material. The 2:1 molar ratio has exhibited an increased strain to failure with increased cure time, whereas the 1:1 molar ratio exhibits a decreased strain to failure. The previous experiments in chapter 5 showed that there was little effect on strain to failure, within experimental boundaries.

It can be seen that there is a large spread of data with the results of strain to failure from the 2:1 ratio cured for 30 minutes. Therefore the results should be considered carefully, although they do seem to show an increase in strain with cure time.

This investigation has shown that some samples of ELO-based resin material that are cured at 150 °C for 20 minutes can have higher peak stress and Young's Modulus than samples cured for 30 minutes. The purpose of this investigation was to assess if energy savings could be made by curing the ELO-based resin material for less time that originally predicted. It seems that 20 minutes is sufficient time for curing of the material at 150 °C.

The effect of the mechanical properties on the flooring can again be assessed through the use of a complement of flooring tests. However, this is not necessary since the previous investigation has confirmed that changes in mechanical properties as a result of processing, will affect the flooring tests in a similar way.

The samples that will be taken forward for the next part of the investigation are those samples that have been cured for 20 minutes. In some cases the samples that have been cured for 30 minutes will also be used for comparison purposes.
6.6 Assessing the Effect of Addition of Filler

6.6.1 Introduction

Samples of material were manufactured that included pre-consumer recycled filler. The manufacture of these samples was described in section 6.2. Since large amounts of voids are present in the filled ELO-based resin material, it is not practical to conduct tensile tests on the samples. However, some indication was required of performance to be expected in use before the samples were to be placed in-situ as a floor. Therefore the samples are subjected to 400 cycles of a Lisson-Tretrad test. The samples chosen were:

- 2:1 molar ratio, cured at 150 °C for 20 minutes with 25 wt% filler
- 2:1 molar ratio, cured at 150 °C for 20 minutes with 50 wt% filler
- 1:1 molar ratio, cured at 150 °C for 20 minutes with 25 wt% filler
- 1:1 molar ratio, cured at 150 °C for 20 minutes with 50 wt% filler
- 2:1 molar ratio, cured at 150 °C for 20 minutes with no filler (comparison)
- 1:1 molar ratio, cured at 150 °C for 20 minutes with no filler (comparison)

It was supposed that the samples may lose material during the wear cycle. One way of assessing this would be to assess the mass of material lost during the trial. Therefore the mass of the samples was measured before and after testing.

6.6.2 Results

The samples showed no appreciable loss of mass during the trial. The results are shown in the table below.

<table>
<thead>
<tr>
<th>Molar ratio</th>
<th>Filler (wt%)</th>
<th>Surface</th>
<th>Mass before trial (g)</th>
<th>Mass after trial (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2:1</td>
<td>0</td>
<td></td>
<td>125.65</td>
<td>125.69</td>
</tr>
<tr>
<td>2:1</td>
<td>25</td>
<td>U</td>
<td>113.93</td>
<td>113.93</td>
</tr>
<tr>
<td>2:1</td>
<td>25</td>
<td>D</td>
<td>104.90</td>
<td>104.87</td>
</tr>
<tr>
<td>2:1</td>
<td>50</td>
<td>U</td>
<td>121.35</td>
<td>121.34</td>
</tr>
<tr>
<td>2:1</td>
<td>50</td>
<td>D</td>
<td>139.03</td>
<td>138.99</td>
</tr>
<tr>
<td>1:1</td>
<td>0</td>
<td></td>
<td>101.25</td>
<td>101.24</td>
</tr>
<tr>
<td>1:1</td>
<td>25</td>
<td>U</td>
<td>135.32</td>
<td>135.32</td>
</tr>
<tr>
<td>1:1</td>
<td>25</td>
<td>D</td>
<td>138.41</td>
<td>138.42</td>
</tr>
<tr>
<td>1:1</td>
<td>50</td>
<td>U</td>
<td>109.25</td>
<td>109.28</td>
</tr>
<tr>
<td>1:1</td>
<td>50</td>
<td>D</td>
<td>112.21</td>
<td>112.20</td>
</tr>
</tbody>
</table>

Table 6.2. Results of mass lost during Lisson-Tretrad test
The results from the Lisson-Tretrad are described in the next section. They are graded visually, divided into 5 “ratings”, where 5 is suitable for heavy contract use, 4 is suitable for medium contract use, 3 is suitable for light contract use and 1-2 are domestic ratings reserved for the home market. As defined in section 6.2 the surface that was in contact with the air during the manufacturing phase is described as up (U) or face down (D).

<table>
<thead>
<tr>
<th>Molar ratio</th>
<th>Filler (wt%)</th>
<th>Surface</th>
<th>Structure</th>
<th>Shade</th>
<th>Overall change in appearance</th>
</tr>
</thead>
<tbody>
<tr>
<td>2:1</td>
<td>0</td>
<td></td>
<td>4.5</td>
<td>4.5</td>
<td>4.5</td>
</tr>
<tr>
<td>2:1</td>
<td>25</td>
<td>U</td>
<td>5.0</td>
<td>4.5</td>
<td>5.0</td>
</tr>
<tr>
<td>2:1</td>
<td>25</td>
<td>D</td>
<td>4.0</td>
<td>3.5</td>
<td>4.0</td>
</tr>
<tr>
<td>2:1</td>
<td>50</td>
<td>U</td>
<td>4.5</td>
<td>4.0</td>
<td>4.5</td>
</tr>
<tr>
<td>2:1</td>
<td>50</td>
<td>D</td>
<td>4.0</td>
<td>3.5</td>
<td>4.0</td>
</tr>
<tr>
<td>1:1</td>
<td>0</td>
<td></td>
<td>3.5</td>
<td>3.5</td>
<td>3.5</td>
</tr>
<tr>
<td>1:1</td>
<td>25</td>
<td>U</td>
<td>4.5</td>
<td>4.0</td>
<td>4.5</td>
</tr>
<tr>
<td>1:1</td>
<td>25</td>
<td>D</td>
<td>4.5</td>
<td>3.5</td>
<td>4.0</td>
</tr>
<tr>
<td>1:1</td>
<td>50</td>
<td>U</td>
<td>4.5</td>
<td>4.5</td>
<td>4.5</td>
</tr>
<tr>
<td>1:1</td>
<td>50</td>
<td>D</td>
<td>4.5</td>
<td>4.0</td>
<td>4.0</td>
</tr>
</tbody>
</table>

Table 6.3. Results of visual assessment of Lisson-Tretrad test

6.6.3 Discussion

During this test, the samples were subjected to a particular type of wear that involved a ‘scuffing’ motion, designed to be similar to footfall. The surface of the samples remained smooth due to the combination of this action and the absence of any sharp instruments that may cause scratches. During this test, there appeared to be minimal loss of material from the surface of the samples.

The measurements of mass lost during the trial show that no appreciable amount of material was lost during this trial. The start and end weights are all within 0.05g of each other. Some samples appeared to have gained a small amount of mass and others lost this amount. Given that the samples were secured to the testing apparatus using double-sided tape, which could leave behind a small amount of residue, or removed a small amount of material upon separation, this could have reasonably explained this small effect. Therefore the measurement of mass lost has not added a great deal to this investigation.
The results of visual assessment show that the U samples have performed better in this trial than the D samples. They still appear glossy after this trial and therefore have achieved better scores for overall appearance.

There is little difference that can be detected between the filled samples that would give an indication whether a greater or lesser amount of filler would be beneficial. However, it should be noted that the unfilled samples have performed slightly poorer in these tests. This could be attributed to the differences in colour between filled and unfilled samples as the light colour of the unfilled samples will exaggerate many flaws in the samples that occur as a result of testing.

It should be noted that the scores for the samples without filler differ only slightly to those given in section 6.4.3. The samples were tested and graded independently for this testing cycle and it can be seen that there is good agreement using this visual assessment grading method.

There are other methods that may be used to measure the change of appearance of a material over time. One method that could potentially be used is the measurement of colour change. This is described in the next section.

6.7 Effect of Wear on Colour Change

6.7.1 Introduction

The Lisson-Tretrad test described in the previous section is a useful indicator of wear. Normally the sample is assessed visually after 400 cycles and then this assessment may be repeated after 2,200 cycles. However, in order to observe a greater degree of accelerated wear, a larger number of cycles are required. Therefore the samples are measured and photographed at the 400 cycle stage and then every 600 cycles until clear signs of accelerated wear are seen such as the removal of surface material on all the samples.

The samples that were tested in this regime were used in the previous section. They were both filled and unfilled to allow comparison since the filled samples were darker in colour. They were:

- 2:1 molar ratio (diacid:ELO), cured at 150 °C for 20 minutes (Sample A)
- 1:1 molar ratio, cured at 150°C for 20 minutes with 50 wt% filler, with surface exposed to air during manufacturing placed down (Sample B)
- 1:1 molar ratio, cured at 150°C for 20 minutes with 50 wt% filler, with surface exposed to air during manufacturing placed up (Sample C)
- 1:1 molar ratio, cured at 150°C for 20 minutes with 25 wt% filler, with surface exposed to air during manufacturing placed down (Sample D)
• 1:1 molar ratio, cured at 150°C for 20 minutes with 25 wt% filler, with surface exposed to air during manufacturing placed up (Sample E)
• 1:1 molar ratio, cured at 150°C for 20 minutes (Sample F)

The samples are shown in figure 6.5.

Figure 6.5. Lisson Tretrad test with samples of the biopolymer system undergoing testing

The results from this test regime are given in the next section.

6.7.2 Results

After 8,200 cycles the samples were not destroyed, although there were clear indicators of wear and therefore the testing was suspended. This resulted in a set of 14 results, which was considered sufficient. The results for L, a and b values were used to calculate the $\Delta L$, $\Delta a$ and $\Delta b$ values from the unworn samples. These were in turn used to calculate a value for $\Delta E$. The results are shown in figure 6.6 below.
Figure 6.6. Graph showing AE values of light measured during Lisson Tretrad test
6.7.3 Discussion

If figure 6.6 is examined it can be seen that the samples all change colour during the course of the wear trial. The unfilled samples (A and F) appear to suffer the greatest colour change from the original sample colour. It could be seen visually that this was because the clear samples were accumulating dark soil from the dark-coloured filled samples. Since the samples are light in colour, this may also be expected in practice as soiling would be a darker colour.

It can be seen that the samples that were placed with the smoother side down (B and D) had the least colour change during this trial. It could be summarised that these samples did not have a top surface to wear away, to expose the bulk of the material. The surface that was already exposed was very similar in structure to the rest of the material. Therefore, when the sample was worn away, there would be a less dramatic colour change.

The samples that were placed with the smooth side exposed (that which was exposed to air during manufacturing and allowed the air bubbles to escape) were samples C and E. The samples seemed to have a large amount of colour change during the trial, although it appeared that this levelled off after a time. This would corroborate the theory that a large amount of colour change is due to the initial wear of the surface.

6.8 Stain Resistance

6.8.1 Introduction

Staining of floor coverings by spilt beverages is a common problem for flooring products in-situ and it is likely that the spillage may not be cleaned immediately. An assessment of staining by some common beverages is normally used by InterfaceFLOR using in-house tests developed for textile and other floor coverings. However, since the test method uses a large volume of liquid, the test method was modified for this investigation.

6.8.2 Test Method

At InterfaceFLOR solutions of coffee and a proprietary blackcurrant juice are normally used to provide staining solutions. They are chosen as they have been shown to provide the most staining; coffee has disperse dye characteristics, whilst the blackcurrant has acid dye characteristics. Past testing regimes have identified the brands that provide the most staining.
For the standard InterfaceFLOR tests 22.5 g of coffee is measured into a flask and then mixed with 100 ml of tap water which is hot to the touch. 10 ml of blackcurrant juice is also mixed with 90ml of water, to provide a 100ml staining solution (Mantle, 2007). A spot of each stain is placed on the sample shown schematically by the diagram below.

Figure 6.7. Schematic diagram of application of blackcurrant and coffee stain for stain resistance tests

Figure 6.8. Schematic diagram of stain resistance tests, showing staining liquid removed by hot water
When the coffee and blackcurrant mixtures are applied to the carpet tile face they are absorbed by the fibres on the face. The stains are then left at room temperature until they are dry to the touch, normally after a period of 48 hours. After this period, half the stains are removed using distilled hot water until the water runs clear. The two stains are then compared using a grey-scale and graded by fully trained assessors from 1-5, where 5 is the best performing.

The filled samples were darker in colour than the transparent unfilled samples. Although filler was not expected to have a major influence on stain absorption, the effect of colour would be significant. A sample of filled ELO-based resin material was therefore compared to a sample of unfilled material.

Since the ELO-based resin material to be tested has a smooth surface, it is unlikely that the material will absorb the stain mixtures to the same degree as carpet tile. Therefore a smaller volume of stain mixture was used, at 10 ml. In order to make the staining tests comparable, the staining mixtures used were more concentrated. Therefore 22.5g of granulated coffee was mixed with 10 ml of hot water and the blackcurrant was used in concentrated form.

Since the stains were not fully dry after the specified 48 hours, they were left for a further 3 days before the results were assessed.

6.8.3 Results

The samples were photographed and shown in figures 9-16 below.

![Blackcurrant stain](image1.png) ![Coffee stain](image2.png)

*Figure 6.9. Stains applied at beginning of test on unfilled sample (blackcurrant on left, coffee on right)*
Blackcurrant stain

Coffee stain

Figure 6.10. Stains after 5 days of drying on unfilled sample

Figure 6.11. Close up of blackcurrant stain after 5 days, showing stain on top surface of unfilled sample

Figure 6.12. Close up of coffee stain after 5 days, showing stain on top surface of unfilled sample
Figure 6.13. Stains on unfilled sample after application of hot water to the outside edge

Figure 6.14. Stains applied at beginning of test on filled sample (blackcurrant on left, coffee on right)
6.8.4 Discussion

For this particular type of flooring the staining solutions were not absorbed. It can be seen that they remain on the surface of the samples. The staining solutions become more concentrated as the water is evaporated. Hot water running over the samples results in the staining solutions dissolving back into solution and being removed from the samples readily.
The results of the preliminary stain resistance tests are promising. The results indicate that the material does not readily absorb either of the dyes and they would receive a 'best performance' grading for this test, i.e. a score of 5.

The effect of filler was mostly to obscure the colour of the samples since it was a dark grey colour. This had the result that the samples appeared to perform better in this test, although both results were 'best performance'.

Since the staining solutions were removed relatively easily via the use of flowing hot water, it could be inferred that removal of staining material on the surface of the system would be expected under normal cleaning regimes. Therefore this material could be expected to endure normal amounts of daily dirt in practice.

6.9 Flammability

6.9.1 Introduction

One of the most important characteristics to be considered for a floor is safety in use and one of the most stringent safety requirements in the construction industry is the flammability of a material (HSE, 2003). There are a number of British Standard tests that describe ways in which the flammability of a flooring material can be assessed. Load bearing elements can be assessed with BS EN 1365-2:2000. The burning effect on the flooring and consequential spread of flame caused by a radiant panel heat source is assessed using BS EN ISO 9239-1:2002. The effect of a small source of ignition can be measured using a test set out in BS 4790:1987 (known as the hot metal nut test). The later is that most commonly used at InterfaceFLOR for quality assurance purposes and testing of new products and so will be used for this project.

The hot metal nut test was designed originally to simulate conditions that may be expected in use, in a similar way to the other flooring tests described. In this instance, the situation that is being simulated is the ejection of a hot coal from a fire onto the flooring.

Since the purpose of this investigation is to examine if the ELO-based resin material can replace other flooring material, it is prudent to compare the characteristics of the material with those that were obtained from the material to be replaced. Samples of biopolymer material were therefore manufactured, both with and without filler and tested using this method. The results were then compared to the results obtained from the Interlock tile and PVC backing material.
6.9.2 Test Method

The sample is held in a ventilated test chamber via the use of a clamping ring. A 30 g hot metal nut, as specified in BS 6105 is heated to a temperature of 900 ± 20 °C in a muffle furnace. The hot nut is placed on the surface of the sample within 3 seconds of removal from the furnace using crucible tongs. The sample may flame or smoulder during this time as shown in the photograph below.

![Hot metal nut test](image)

*Figure 6.17. Hot metal nut test*

The nut is then removed from the surface of the sample after a time of 30 ± 2 seconds. The sample remains in the chamber until all effects of ignition have ceased. The radius of the circle that just contains the affected area on the use-surface is then measured.

The samples measured were similar to those used in previous experiments and were:

- ELO-based resin material with a 1:1 molar ratio, cured at 150 °C for 20 minutes
- ELO-based resin material with a 1:1 molar ratio and 25 wt% filler, cured at 150 °C for 20 minutes
- ELO-based resin material with a 1:1 molar ratio and 50 wt% filler, cured at 150 °C for 20 minutes
- ELO-based resin material with a 2:1 molar ratio, cured at 150 °C for 20 minutes
- ELO-based resin material with a 2:1 molar ratio and 25 wt% filler, cured at 150 °C for 20 minutes
- ELO-based resin material with a 2:1 molar ratio and 50 wt% filler, cured at 150 °C for 20 minutes
- PVC Interlock tile
- Back of PVC-backed carpet tile

The results are given below.
6.9.3 Results

Table 6.4 below shows the measured radius of affected area measured using a steel ruler with an error of ± 0.5 mm.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Filler (wt%)</th>
<th>Radius of affected area (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1:1 molar ratio</td>
<td>0</td>
<td>20</td>
</tr>
<tr>
<td>1:1 molar ratio</td>
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<td>Back of PVC-backed carpet tile</td>
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*Table 6.4. Results of hot metal nut test*

6.9.4 Discussion

BS 5287: 1988 describes the way in which the results from the hot metal nut test should be assessed. If the radius of affected area is shown to be below 35 mm, the sample is defined to have a “low radius of ignition when tested according to BS 4790”. In each of the samples tested above, the radius of affected area was below 35 mm. Therefore all samples tested would have a low radius of ignition, according to this test.

It should be noted that the effect of filler in these tests has been to reduce slightly the radius of affected area. This is to be expected since the filler is inert. The effect of a larger molar ratio of components, i.e. more cross-linker, also had the effect of reducing the radius of effect area. It is possible that this is because there is less residual oil in this mix, which may be in excess at the 1:1 molar ratio and is the most flammable component.

The PVC backing material contains filler, which would be considered inert. The backing also contains polypropylene and fibreglass. However, in practice it is the surface of the carpet tile that provides the flammability resistance since heat is normally applied from the surface of a flooring material and the backing is rarely affected by direct heat. In this experiment it can be seen that this sample passes the flammability test in a similar way as the comparison samples.
The Interlock tile contains no filler, but is used as a flooring material and would also have passed flammability testing previously. Since the tile passes with a similar radius of affected area as the samples of ELO-resin material, this indicates that these samples may be expected to perform similarly well in other flammability tests.

The test results indicate that if any of the materials “are ignited from a small source, such as a lighted match or glowing coal, it will not spread flame under normal conditions in the absence of supporting radiation.” (BS 5287:1988)

This test is not definitive for examining the fire safety risk of a flooring material, although it could be indicative of results to be expected from other tests. Since the ELO-based resin material has not been identified as a fire safety hazard at this stage, it can be investigated further.

6.10 Conclusion

The flooring tests that have been undertaken on this new material are extensive. The flooring tests have confirmed that which was predicted by the tensile tests. It is therefore suggested that these tests be used as a proxy for future flooring materials, in order to avoid the extensive flooring testing regime required for all combinations of processing parameters on the material.

The set of flooring tests have shown that the material manufactured from ELO and the cross-linker can pass a heavy contract rating. The ELO-based resin material is therefore fit for the purpose of providing a flooring surface, albeit at different ratings depending on processing parameters.

The accelerated wear tests described above were designed to gauge whether colour measurement would be a prudent way of measuring wear of a sample in-situ. It can be seen from the results that there are changes in the colour values with increased wear. The results of the colour measurement trial show that measuring colour can be an effective way of measuring soil or wear, although the relationship is not yet fully understood. Therefore this method will be used for the flooring trials and the results shown in the next chapter. Visual assessment and documentation are recommended in conjunction with this technique.

The flooring tests described in this chapter have given results that do not preclude flooring trials. Therefore the next stage of this investigation is to conduct full-scale flooring trials with this ELO-based resin material.
Chapter 7 Flooring Trials

7.1 Introduction

When new flooring products are constructed, e.g. with new yarn constructions, backing systems or surface material, they are comprehensively tested to ensure that they meet industry quality standards. This involves completing a full regime of flooring tests (described in Chapter 2). The tests, designed to simulate conditions to be expected in use, were used on the ELO-based resin and the PVC tile and described in the previous chapter.

In addition to the standard tests, a new flooring product is subjected to in-situ testing in a high traffic area. This is intended to verify the performance to be expected in practice, predicted by the flooring tests. This has been the established practice within the carpet industry and at InterfaceFLOR since the inception of the company.

An area of floor used to assess these flooring trials at InterfaceFLOR is shown in the photograph below. Here many different types of carpet tile are placed together, tested and assessed. The samples used are a standard tile which is 50 cm x 50 cm. They are left in-situ for a standard six month period, where they are subjected to regular foot traffic and are cleaned using a vacuum on a weekly basis. The samples are observed on a daily basis since they are situated near the laboratory, but assessed visually at the end of the trial for changes in appearance.

Figure 7.1. Flooring trial area
A number of ELO-based resin samples were manufactured for testing in this trial area. The manufacturing process was the same as that described in the previous chapter. Greater detail of the sample size and manufacturing method is given in section 7.2.1. The samples were secured in place, surrounded by a material of similar height and characteristics.

Methods of non-perturbative, in-situ measurement were considered. Visual assessment is one method that is already used at InterfaceFLOR at the end of the trial period and in-line with the other tests used, this was used again. However, due to the rigour expected for this EngD project, it was decided that photography should be used to provide a permanent record of the changes in appearance of the material over time. A record of the samples using photography on a monthly basis was undertaken. Since most flooring material shows little variation over the period of 6 months, it was decided that a period of 1 month would be the minimum over which differences in the samples might be observed. This is described in section 7.2.2.

It was not expected that there would be a change in mass or thickness of the samples that would be detectable over the trial period. However, to record this would entail removing the samples from the floor regularly and therefore risking damage to the samples during this removal process. Therefore this method was not used.

It was shown from the work in the previous chapter that colour measurement may be used to signify visual changes in appearance. This method does not entail any movement of the samples and may be performed in-situ. Therefore this method was chosen in addition to visual assessment.

It was predicted that the colour of the samples would vary with time as there may be damage to the material and colour change as the material ages. This was described in the previous chapter where it was shown that accelerated wear can result in a change in colour measured. The samples were subjected to the same regular foot-traffic and cleaning cycles on a daily basis as other flooring samples. Large particles of loose soil could be picked up by the vacuuming process, although some smaller soil particles could remain within the surface crevasses of the material. These could change the colour of the samples, in the same way as carpet retains soil over time. Signs of soil that can be seen visually include darkening or lightening of areas of the samples and prints resulting from traffic. The results from visual inspection are shown in section 7.3 and discussed in section 7.4. Section 7.5 describes the conclusions from this trial. The test method is described in the next section.
7.2 Test Method

7.2.1 Introduction

The results from the flooring trial are intended to confirm the results that were predicted from the flooring tests, since the tests are designed to simulate that which would be expected in practice. Each flooring test is designed to simulate the effects of different types of wear. For example, the Lisson-Tretrad test simulated scuffing and the Vetterman drum tests simulated multiple impacts. It is possible that multiple types of wear will have some influences on the structure of the material that are different to that applied during the testing. Therefore in-situ testing is essential to the ELO-based resin material to verify its actual performance as a flooring material.

There were a large number of samples available from the tests described in the previous chapter. The 'best' and 'worst' unfilled samples that were used for the previous flooring trials were used for this trial. These two samples were chosen in order to provide the expected maximum difference in performance under wear conditions.

In Chapter 6 it was shown that samples were sufficiently cured after a period of 20 minutes, so these were also used in the trial.

A number of samples were also manufactured that included the recycled filler material, (Chapter 3). Filler is normally added to PVC in order to increase bulk, whilst reducing cost. Filler was added to the samples at 25 wt% and 50 wt%, as in the previous chapter. It was added to the 'best' and 'worst' samples and again cured at 20 minutes.
During the manufacturing process of the ELO-based resin material, one surface of the sample was in contact with the Teflon-coated metal container used to hold the sample, whilst the other surface was exposed to the air. When recycled filler was used in the samples there was invariably a small amount of air incorporated into the samples, due to the mixing of uncured components. Despite efforts to minimise this through careful mixing, some air remained. Also despite the addition of heat during the curing cycle with consequent slight reduction in viscosity of the system, there were some air bubbles that remained in the filled samples. They could leave the mixture at the surface of the sample in contact with the air, but they remained throughout the sample and at the surface in contact with the metal container. This was because the mixture remained too viscous for the bubbles to escape before the sample set. There is also the possibility that the surface of the metal container provides a source of nucleation for bubble formation that can arise as a result of the action of the acid on the filler, producing CO₂. Therefore the two surfaces were compared with each side laid up separately during the trial.

The surfaces of the unfilled samples, cured at 20 minutes, were also compared separately, although they did not appear to be different through visual inspection. This is for completeness, in order to confirm the theory that the surface of the unfilled sample does not affect performance in-situ.

The samples were labelled in the following way:

00.00/111/22m/AAf/Y

Where:

- 00.00 is the molar ratio of diacid to 1 mole of ELO
- 111 is the curing temperature in °C
- 22m is the curing time in minutes
- AAf indicates the mass of filler used (where none is used this will read 000, f is indicative of the type of filler used)
- Y indicates whether the surface of the sample in contact with the air during the manufacturing of the samples was laid up (U) or down (D)
PVC samples were also included in the trial for comparison. The PVC Interlock tile was used as a standard in the flooring tests and the tensile tests as ‘best performance’ and therefore it was appropriate to use them again as a standard. The PVC backing system is also used as a comparison, although it has not been used as a stand-alone flooring product. This was for two reasons; firstly the ELO-based resin material has potential to be used as a backing material and should be compared against current product, secondly the PVC-backing was never intended to be used as a stand-alone flooring material since has provided the non-wear surface of carpet tile may be expected to perform differently in these trials to the other samples under test. These samples were placed in the trial area.

The samples needed to be secured to the floor in a way that would not interfere with the regular foot traffic. The samples needed to be held in place securely, such that they could not be lifted during normal use, whilst avoiding providing a trip hazard. It was therefore decided to glue the samples to the floor using a strong adhesive, typically used for securing linoleum and PVC material. An attempt was made to remove the samples at the end of the testing period.

The ELO-based resin samples needed to be set into a larger area of material, since the size of samples that could be manufactured using the manufacturing technique were limited. The surrounding material would also constrain the material under test. Linoleum was used as it is a resilient flooring, of similar thickness to the ELO-based resin material and readily available. Linoleum has also been shown to have properties of the same magnitude as the ELO-based resin material, with a Young’s Modulus and tensile strength in the single figures and a strain in double or triple digits (Biagiotti et al, 2004).

The thickness needed to be similar, within 1 or 2 mm, to avoid creating a trip hazard. It is possible that this slight variation in thickness would result in the leading edge of the sample receiving more wear, although this was not seen with visual assessment. The linoleum was provided in tiles, with slightly differing colours and used to surround the ELO-based resin samples. It was also glued to the floor with the adhesive.

The sample size was also chosen to have a diameter of 140 mm as this would be large enough to exhibit visual signs of differences in performance, provide a large enough size for colour measurement and is also sufficient relative to a typical shoe sole for the surrounding material not to influence the forces causing wear on the specimen. They were cut using a standard circular press and set in the linoleum surround.

The samples were placed in the same high traffic environment as other flooring products under test. The completed area is shown in figure 7.2.
Figure 7.2. Trial area of samples of ELO-based resin material, with PVC samples shown to the left

The diagram and photograph below shows the way in which the samples were laid out.
Figure 7.3. Schematic of trial area of samples

Figure 7.4. Photograph of trial area
The samples were cleaned on a weekly basis, in the same manner as other flooring trials, using a standard vacuum cleaner. It was expected that there would be a change in visual appearance that could be detected by the human eye after the 6-month trial period. It was decided that this would not be sufficient for this project and therefore the samples were assessed on a monthly basis. This time period is chosen, as although there were not visual changes in appearance expected during this time period, there may have been recordable changes. Photography is one method that is used to capture change in visual appearance of the samples and this is described below.

7.2.2 Assessment Method

Photography is a useful tool in visual assessment. It ensures that a consistent record can be kept of any visual assessment made and is normal practice in the carpet industry to grade samples at the end of testing. For this project it is also useful to have some record of the visual changes throughout the trial and therefore photography was used.

On a monthly basis, photographs of the samples were taken. Each sample was individually photographed using a Kodak EasyShare DX 7630 and a Schneider-Kreuznach lense in close-up mode, without flash. Each picture was recorded using 6 megapixels. The photographs were taken at an angle of approximately 70° to the horizontal, in order to reduce the specular reflection from ambient lighting on the sample, which may have in turn masked surface imperfection.

A complete photographic record of the 6-month trial is appended in the Appendix A.

After the trial period, the samples were also visually assessed by three professional flooring assessors along with the author of this report. Every assessor had undergone the same training that would allow them to assess the changes in the appearance of a carpet tile subjected to this type of trial. Two of the assessors (A and B) were experienced in this type of assessment and would conduct testing on a daily basis. The other assessors (C and D) were trained, but not well-experienced in this type of assessment and therefore the results for the experienced assessors and the in-experienced assessors are shown separately.
The grading is based on the evaluation used for soft flooring, described in the previous chapter, with the standard three categories. It was decided that since this flooring has a smooth appearance an additional category of ‘surface scratches’ was required. Each sample was given a grading from 1-5, where 5 is the best to be expected from the flooring. Half marks were allowed. For carpet tiles there are standard test results that are held for comparison purposes. With this particular material, there are no such standards and therefore discretion is used along with the linoleum surround, useful as a material for comparison purposes. The categories used are:

- **Shade** - the amount of discolouration of the sample, assessed using a standard grey-scale
- **Structure** - the change in structure of the sample. A lower grade results if a large amount of material on the sample has been worn away
- **Surface scratches** - the appearance of the surface of the sample. A lower grade results if there are a number of scratches on the surface
- **Overall** - the overall appearance of the sample

It was not necessary to give a visual assessment and full grading of each of the samples on a monthly basis as they changed little visually within this time frame. As previously stated, the six-month period used was the standard used for this type of trial where visual changes can be expected.

Samples were also assessed using the colour measurement method, described in section 6.7, using a Chroma Meter CR-210. These results were already averaged over the sample area and therefore single results are recorded with no error bars available. The results for \( \Delta E \), the overall change in colour, were calculated and shown in the next section.

### 7.3 Results from flooring trials

Photographs 5-13 below show the samples at the beginning and end of the trial. Higher resolution photographs are appended in Appendix A, taken monthly. Samples that were filled are shown with the surface that was in contact with air during the manufacturing process at the top of the photograph. The samples were assessed on a monthly basis and visual assessment indicated that after the initial period of six months, there was very little change in appearance for most of the samples. Therefore the samples were left for a further two months, to project end.

Visual inspection indicated that the sides of the sample did not receive more wear than other areas. Some of the photographs show a small amount of shine reflected as a result of overhead light. Since at InterfaceFLOR the lights are motion-sensitive it was not possible to remove this for photography purposes.
Figure 7.5. Photographs of sample 01.00/150/20m/50f, before and after in-situ flooring trials

Figure 7.6. Photographs of sample 01.00/150/20m/25f, before and after in-situ flooring trials
Figure 7.7. Photographs of sample 02.00/150/20m/25f, before and after in-situ flooring trials

Figure 7.8. Photographs of sample 02.00/150/20m/50f, before and after in-situ flooring trials
Figure 7.9. Photographs of sample 01.00/150/30m/000 (bottom sample) and 02.00/150/30m/000 (top sample), before and after in-situ flooring trials

Figure 7.10. Photographs of sample 01.00/150/20m/000, before and after in-situ flooring trials
Figure 7.11. Photographs of sample 02.00/150/20m/000, before and after in-situ flooring trials

Figure 7.12. Photographs of sample of PVC flooring (Interlock), before and after in-situ flooring trials
Figure 7.13. Photographs of sample of PVC-backing of carpet tile, before and after in-situ flooring trials

The final assessment of change in appearance, given by the experienced assessors, A and B, are shown in table 7.1 and 7.2. These are listed in the order in which they appear in the trial. The average results from the inexperienced but trained assessors, is given in table 7.3. The average of all the assessments, including the author of the trial and the assessor that conducts these tests on a less-regular basis, are show in table 7.4.
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<thead>
<tr>
<th>Sample Number</th>
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Table 7.1. Results of visual assessment of samples by assessor A, where 1 is lowest and 5 is highest grade, half marks allowed
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*Table 7.2. Results of visual assessment of samples by assessor B, where 1 is lowest and 5 is highest grade, half marks allowed*
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<td>5.0</td>
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<tr>
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</tr>
<tr>
<td>01.00/150/20m/000/D</td>
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<tr>
<td>01.00/150/20m/000/U</td>
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*Table 7.3. Results of visual assessment of samples by assessors C and D, where 1 is lowest and 5 is highest grade, half marks allowed*
<table>
<thead>
<tr>
<th>Sample Number</th>
<th>Shade</th>
<th>Structure</th>
<th>Surface Scratches</th>
<th>Overall Grading</th>
</tr>
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<tr>
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<td>5.0</td>
<td>4.0</td>
<td>4.0</td>
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<tr>
<td>PVC Backing</td>
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<td>3.5</td>
<td>2.5</td>
<td>3.0</td>
</tr>
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<td>3.5</td>
<td>4.0</td>
<td>3.5</td>
</tr>
<tr>
<td>01.00/150/20m/50f/U</td>
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<tr>
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<td>02.00/150/20m/000/U</td>
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<td>4.0</td>
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</tr>
</tbody>
</table>

*Table 7.4. Results of average of all visual assessment of samples, where 1 is lowest and 5 is highest grade, half marks allowed.*

Measurements of colour were also taken on a monthly basis. The results are shown graphically below. It should be remembered that a value of $\Delta E$, less than 1 is barely perceptible to the trained human eye and the casual viewer can typically differentiate between colours 5-6 $\Delta E$ apart (Colors, 2007). Each graph is shown on a scale of 0-8, for easier comparison, with the point measurement shown. Some of the results shown on the graphs appear clustered below a $\Delta E$ of 1, which is not significant for visual assessment purposes. The samples are labelled in the same manner as before.
Figure 7.14. Graph showing change in $E$ values of filled samples, with the surface exposed to the air during manufacturing placed down, with time.

Figure 7.15. Graph showing change in $E$ values of filled samples, with the surface exposed to the air during manufacturing placed up, with time.
Figure 7.16. Graph showing change in $E$ values of unfilled samples, with 1:1 molar ratio, with time

Figure 7.17. Graph showing change in $E$ values of unfilled samples, with 2:1 molar ratio, with time
7.4 Discussion

7.4.1 Comparison of Methods Used

There were three types of measurement used in this testing regime. The visual assessment method is used for standard testing, with the added category of ‘surface scratches’, deemed to be important to assess for this type of resilient flooring material. It is important to compare the results obtained from the different techniques before comparing samples within the trial, in order that the techniques may be validated.

At the end of the trial, the samples were given four grades based on appearance by two assessors who conduct this kind of grading on a daily basis. The individual results from these assessments are shown in table 7.1 and 7.2. These results show close correlation, with a maximum difference of 0.5 across all categories. This is hardly surprising since these assessors work together closely on grading carpet tile on a daily basis. It is worth noting that even with a new category of ‘surface scratches’ the experienced assessors can still agree on results.
The average results for the trained, but inexperienced assessors are given in table 7.2. The results show close correlation with those from the experienced assessors. Although one set of results tended to be consistently higher than the other, they were still ranked in the same manner.

The average of the results from all four assessors is given in table 7.4. The results showed that the average of all results is similar to those from individual assessors. The ranking for each sample was the same, whether the assessor was experienced or not.

The results from this investigation show that visual assessment is a useful tool in evaluating flooring samples under test. A small amount of training is required in order to be able to rank flooring materials. Experience in visual assessment grading will produce more consistent results and therefore this should not be underestimated for future work.

Although the actual assessment results varied between assessors, there was general agreement in the ordering of the samples within each category. Therefore the average result shown can be useful in identifying the best and worst samples.

It was expected that the Interlock tile would be the best performing under this test regime. This is because the tile has already been sold commercially as a resilient flooring material and is known to perform well in use.

Figure 7.12 shows that although the tile has accumulated a degree of visible soiling during the trial, the structure of the sample remains intact. This is reflected in the visual assessment scores given for this sample. Table 7.1 and 7.2 show that the tile receives good scores from each assessor for structure, surface and overall (4.0-5.0), but is given a decreased mark for shade (3.5).

The visual assessments were in general agreement that this sample was the best for resistance to surface scratches and structure, with a grade of 4 overall. There were a number of other samples that received these grades and sample 01.00/150/20m/25f/U received higher average scores for visual assessment, which was reflected in the colour change measurement. This is shown in figure 7.15 where it can be seen that the ΔE for this group of samples does not reach the visually significant level.
The sample that received one of the lowest grades overall was the PVC backing. Since this was not designed to be used as a stand-alone flooring material, this result is not unexpected. Figure 7.13 shows that the structure of the sample has been affected and this is reflected in the visual assessment results. There is a marked change in colour, giving a ΔE of over 6, which is within the visually identifiable range. Therefore the results for visual assessment and colour change measurement are in agreement.

The most significant result for colour change colour was not for the PVC backing, however. A result of almost 8 ΔE was found for the sample 02.00/150/20m/000/U. This sample also received an unusually poor overall grading at 3.0. The overall average was the same as the PVC backing, with slightly poorer result for shade and a better result for surface scratches.

It can be seen from figure 7.11 that there appears to be some residue on the surface of the sample. This could be as a result of the manufacturing process, although this is unclear. The defect on the surface appears to have retained residual soiling, which has caused the change in colour and the poor visual assessment results. However, the results are in agreement again that this is amongst the two worst samples.

It should be noted that with hindsight this sample should not have been placed on the floor due to this surface defect, which then disrupts the continuity of the results. However, the sample that was placed with this side down and the same defect (02.00/150/20m/000/D) provides meaningful results for comparison purposes with the other samples. This is because it was not expected that there would be a difference with the U and D samples. This will be discussed further in the next section. This result also indicates that a good manufacturing technique is essential for this material to perform.

It can clearly be seen from the figures 14-18 that in May there was a step-change in colour. This was investigated further and it was found that the floor in the laboratory, next door to the samples, was cleaned between the samples being measured in April and May. The photographic record of the samples shows that there was a large amount of soil that appeared between these two measurements, in the form of footprints, roller marks and drips. This step-change can therefore be accounted for with the addition of this soil. This is verified through the examination of the photographs of the samples in April and May, shown below.
It has been noted that there was good overall agreement between the comparison techniques. Therefore the samples that were chosen for this trial will be examined.
7.4.2 Comparison of Performance of Samples under Test

Visual inspection has been useful throughout the in-situ tests in identifying wear on the samples and subsequently the most likely source of damage. There has been a degree of soil that has been retained by the linoleum surround and PVC sample after vacuuming. Dark soil is also evident on the ELO-based resin material samples, although this is less obvious visually due to the dark colour of the filled samples. There is little visual evidence of scratches and scuffs on the surface of any of the materials after 8 months, although there is some evidence of material damage on the PVC-backing. This was to be expected since the material is not intended for use as a flooring surface.

Figure 7.14 shows the filled samples with the surface exposed to the air during manufacturing placed down (D) and figure 7.15 shows these samples cut from the same test piece with this surface uppermost (U). In contrast to the measurements from the flooring tests in the previous chapter, it can be seen that the U samples are exhibiting much less colour change. This is confirmed by the visual assessment as they are the samples that received a better grading. It can be seen that the samples are still glossy in appearance, indicating that the glossy surface has not been worn away to reveal the less glossy main body of the sample. Therefore this colour change is probably not due to wear, but soil accumulation. This is confirmed by viewing the photographs of the samples.

Figure 7.14 shows that there is little difference between the colour change measurements of the D samples. Again this is confirmed by the visual assessment method as each sample received an overall score of 3.5. This appears to indicate that the amount of filler added has not yet had a significant effect on performance during this type of test.

It can also be seen from figure 7.15 that the colour difference for the filled resin samples, U, does not rise much above a ΔE of 1. This implies that the colour difference between the start of the trial and the final results is barely discernable to the trained human eye. The results from visual assessment indicate that these samples were all closely matched on performance. The overall visual assessment results ranged from 4.0 to 5.0, indicating that this barely perceptible change has been noted by the trained human eyes used in this trial.
Figure 7.16 shows the change in colour for the unfilled samples, manufactured with a 1:1 ratio. These data show that there is little difference between the U and D samples in this case, anticipated at the start of the trial. The sample that was cured at 30 minutes exhibits slightly less colour change than the other samples. This colour change is generally less that 1 \( \Delta E \) away from the colour change of the samples cured for 20 minutes. Therefore this result is not yet significant, although this may change with increased trial time. This is confirmed by the results in table 7.1 and 7.2 which show that there is little difference between samples 01.00/150/20m/000/U, 01.00/150/20m/D and 01.00/150/30m/U.

Figure 7.17 shows the difference in colour over time for the unfilled samples, manufactured with a 2:1 ratio. It can clearly be seen from the photograph in figure 7.11 that the D sample, cured for 20 minutes has accumulated a greater amount of soil than the U sample. This was discussed in the previous section. If this information is taken in conjunction with the data in figure 7.16 it can be seen that there is little difference between the wear and soil accumulation of the D and U samples of the unfilled material. There is little difference in the \( \Delta E \) values for samples 02.00/150/30m/U and 02.00/150/20m/U, which would again confirm that the reduced cure time has little effect.

The two PVC samples are shown in figure 7.18. It can be seen that the PVC backing material has the greatest colour change of all the well-manufactured samples (confirmed visually by figure 7.13). The sample has clearly worn. The Interlock tile received a poor grading for shade due to the large amount of soiling visible on the surface although the grading for structure was excellent. The PVC-backing in contrast has performed particularly poorly, with no grading above a 3.5. The Interlock tile has achieved one of the highest gradings and it is clearly fit-for-purpose.

At the end of the trial an attempt was made to remove the samples from the substrate. The samples had been anchored in-situ with a strong adhesive, in order that the samples would not move during the trial. As a consequence of the application of this adhesive the samples could not be removed from the substrate without extensive damage to them. However, visual inspection also indicated that there was little mass lost during the trial.

7.5 Conclusion

The results from visual assessment also show that this can be a useful tool in identifying the performance of material under tests. Experience in this field is advantageous, although not essential. The results from this investigation also show that visual assessment on its own as a tool is sufficient and that the colour measurement may not be required.
The results from visual assessment have shown that there were a number of samples that achieved a similar grading to the sample of Interlock tile for structure, surface scratches and overall appearance, all factors which indicate wear. The colour change measurements have also shown that there were a number of samples that would not differ from their original colour by more than a trained human eye can assess.

The sample that was identified as the best performing during this trial was 01.00/150/20m/25f/U. However, this was not significantly better than any of the other ELO-based resin samples and had slightly improved results in comparison to the Interlock tile. The ELO system is therefore fit for the purpose of providing a flooring surface, albeit at different ratings depending on processing parameters.

This trial was not sensitive enough to establish if the amount of filler in the samples was significant in affecting wear performance. A longer trial period would magnify differences in wear performance and therefore it is recommended that the trials are left for a longer period. It was established that good manufacturing technique is essential for performance. The samples are performing well in the flooring trials and they should be continued for long-term trials in order to establish if a difference can be detected over a greater length of time. This trial could be left in place for several years- for 5 or 10 years that resilient flooring may be expected to be in use before being replaced.

Whilst measuring colour may be a useful quantitative measure of the changes that can be seen happening over time, this has not yet been established. It is not yet clear how the relationship between soil, wear and colour can be measured. The colour change is a factor of both the soil accumulated and wear. This has been confirmed by comparison with the visual assessment techniques. The measurement of colour has been useful in establishing which of the samples have performed better or worse with the samples exhibiting a ΔE of less than 1 performing well in the visual assessments. It therefore seems prudent to use colour measurement in conjunction with the traditional visual assessment techniques.

The system has thus far been shown to be competitive for performance against a PVC tile when used as a flooring material. The complement of tests has shown that the material manufactured from ELO and the cross-linker can provide performance under these trial conditions that is comparative to a PVC tile.
Chapter 8 Concluding Remarks and Further Work

8.1 Introduction

The aim of this project was to explore sustainability within the flooring industry and in particular from the perspective of InterfaceFLOR, a company with a stated mission to become fully sustainable by 2020. This general aim has been met with specific outcomes that contribute incrementally to existing activities and more radically to the future portfolio of InterfaceFLOR.

The first objective of this EngD project was to develop the current InterfaceFLOR flooring product so that it could be manufactured in a more sustainable way. It seemed sensible at this time to evaluate the need that was being fulfilled by this product and therefore the requirements of a flooring consumer were evaluated. This enables understanding of how the current products in the market satisfy these requirements. This has resulted in a diverse range of flooring materials being produced that fulfil these demands in different ways. Further, it has been shown that revolutionary concepts, considered as part of this project, may be accepted by consumers. Following the analysis of the market research this has enabled a brief evaluation of the sustainability credentials of these products and an analysis how the manufacturing techniques and materials used in these products may be transferred to other products to increase their sustainability credentials.

This project was set to improve the current manufacturing process. This involved developing an understanding of the anecdotal evidence provided by the line operators and comparing the results to those obtained through scientific evidence. It was concluded that although this kind of 'soft' evidence can be useful in guiding the direction of work, 'hard' evidence such as observation and measurement are always required and should be gathered with independence and non-bias.
Evaluation of current carpet tile processing was undertaken. The analysis identified faults with the existing process and suitable modifications enabled the process to be improved. The project has facilitated the reduction of environmental impact of the current InterfaceFLOR product via the use of recycled material, whilst retaining performance. This has the result that over 8,000 tonnes of material per annum could be diverted from landfill. There are issues with the delivery and availability of recycled material and it may have to be mixed with virgin content in order to achieve the quantity desired. However, the recycled filler will be launched commercially in the autumn of 2007 and communicated externally to customers shortly after with a guarantee of 33 to 50 wt% recycled content in all product. At current production rates this is over 5,000 tonnes of material per annum being diverted from landfill.

During the course of this project, the drive at InterfaceFLOR shifted so that innovative concepts could be initiated and investigated. This was largely due to the appointment of an Innovations Director, the establishment of the Innovations Workshops, the creation of the Innovations Network and the establishment of the Innovations Pipeline. This in turn, moved the impetus for this EngD project from incremental progress within the company to investigation of revolutionary concepts through partnerships. It is obvious that many of the concepts would have remained abstract ideas were it not for this network of experts and the drive and support from within the company.

The results of the workshops and the network are described and InterfaceFLOR now has a different perspective on innovation. The group of innovators- both internal and external will validate the concepts held in the pipeline. InterfaceFLOR has learned through this process that it is not possible to undertake innovation alone. From the experience of this project, it is clear that freedom of expression, external influence, partnership ownership, responsibility are all required for sustainable innovation to succeed. InterfaceFLOR has also learned through this process that in order for innovation to succeed, it can be less 'successful' in the terms that business is usually measured- return on investment, process improvement, efficiency etc.

As a result of the freedom allowed by InterfaceFLOR, innovative flooring concepts have been created and investigated as part of this project. This has highlighted the need for a variety of products to move towards the overall sustainability objective.
Although flooring cannot be categorised without the traditional flooring tests, this project has identified some tests that may be used as a proxy. These tests may be used for similar systems to that investigated. Oils that have similar chain lengths (linseed and soy bean) could be used with similarly sized cross-linkers to that used in this investigation. Longer-chained oils or cross-linkers would have the result of a larger, more open polymer network which would increase flexibility. The relationship between properties and performance of a floor would then be less certain. Similarly, smaller-chained cross-linkers and oils would result in a closer polymer network and there could be less certainty about the results of flooring tests.

The use of proxy tests has the result that large volumes of material are not required for the tests. Therefore, a larger number of single-material samples can be investigated that have been subjected to different processing regimes and the effects evaluated with greater efficiency.

Included as Appendix B is a copy of the paper to be published in the peer-reviewed journal “Industrial Crops and Products”, published by Elsevier. It contains key conclusions from the most recent work carried out as part of this Engineering Doctorate. It is titled “An investigation of epoxidised linseed oil as an alternative to PVC in flooring applications”.

The resin material was investigated as a flooring product and it was compared to current product. The combination of assessment techniques have similar results and this allows increased confidence in the current visual assessment methods, where it is shown that a combination of experience and training is advantageous. The results from these tests have shown that the resin material could perform well both under flooring tests and flooring trials. This material can pass these tests with a similar rating to the PVC Interlock tile. This investigation shows that this novel resin material can be fit for the purpose of providing a flooring material.

The material has also been considered as part of the backing system for a carpet tile. This investigation is continuing at InterfaceFLOR. This project has ultimately shown that providing a floor can be done in an environmentally considerate way.
8.2 Further Work

As a result of the processing recommendations made and the completion of the investigation of alternative filler, described in this thesis, InterfaceFLOR has invested heavily in machinery that will enable the recycled filler to be used. This includes investment in a sieving system that will remove particles that are above 300 μm from the filler. These particles will then be reduced in size using the new grinding mechanism and returned to the mix. This investment in and installation of machinery has already taken place at Shelf Mills and is under consideration for the other European InterfaceFLOR manufacturing site.

It would be prudent to investigate the cure of the ELO chemically in order to understand the mechanism more fully. This would facilitate the investigation of the cross-linker and the use of catalysts. Investigation of the rheology of the system would also enable greater understanding of the effect of processing parameters on the system. This could take the form of Dynamic Mechanical Rheological Testing (DMRT). For thermosetting polymers, DMRT can measure the rheological changes occurring during the curing reaction as the resin transforms from a low melting solid to a low viscosity liquid, then through the gel point without disrupting the gel structure, and finally to a highly crosslinked, stiff solid.

The ELO-based resin material was originally intended for use as the PAF concept. The major drawback of the material for this concept was the length of time taken to cure at room temperature. Although some catalysts were initially investigated, and were able to reduce cure time, they were not pursued as the cure time of the system was still excessive. There may be other catalysts that able to cure the system in a faster time, which require further research and investigation. The catalysts used for this concept should preferably be from renewable sources. This research is continuing, sponsored by InterfaceFLOR, at York University by members of the Green Chemistry Network.

Although the ELO-based resin has not been investigated as fully as possible, other possible cross-linking agents could also be investigated, such as succinic diacids and anhydrides. Some are becoming available from renewable sources and others may be possible with a significant sustainable content. However, the cross-linker requires only two reactive groups on the molecule that will combine with the epoxide groups on the ELO. Further, other epoxidised vegetable oils need to be evaluated. InterfaceFLOR is in the process of recruiting another Engineering Doctorate research engineer to investigate these options.
It has been shown that heating the separate components of the material before mixing can decrease viscosity of the system. This would be particularly useful when moving to processing on a larger scale. However, the effect of this heating is unknown and therefore requires further investigation. This investigation would also consider the incorporation of greater amounts of filler and the effect of different types of filler.

It is still debatable whether a greater Young’s Modulus, peak stress or strain to failure would be more beneficial for a flooring product and this should be investigated further. This would further validate the use of tensile tests as a proxy test for the regime of flooring tests.

When the material is subjected to wear there is a change in colour measurement that can be seen with time. It is not clear whether this result would be expected for all materials. However, this could be a useful measure for quantifying wear-particularly with InterfaceFLOR’s current product, the carpet tile.

Some carpet tiles are manufactured with white yarn and then dyed after construction. This results in a product that has a coloured surface and a white core. This colour difference after wear testing is currently measured using visual assessment methods and a grey scale where quarter grades are often considered. It is suggested that the colour change due to this wear may be more readily identifiable using the colour change measurement method described in this thesis. This would enable different yarn and print processing techniques to be compared more easily.

The work conducted in this EngD project has produced a novel flooring solution that can fulfil consumer requirements as well as enabling InterfaceFLOR to incrementally improve current product. This work has since been presented to a number of InterfaceFLOR Directors in a series of seminars. As a result of these discussions it was decided to present this work to the InterfaceFLOR Global Backing Group for consideration, along with proof-of-principle prototypes. It was decided that this material had greatest potential as a backing system replacement.

Using the processing parameters defined in this report, an investigation is ongoing to determine the investment required for a new backing line that would incorporate this material. The results of the exploration of the effect of pre-heating the components would be of use to this investigation.
The cost of the material has also been considered and has been investigated with potential suppliers. If all the PVC backing material in the UK is replaced with the ELO-resin material, there are large volumes of material required. Production of the cross-linker and ELO in these types of volumes would enable a competitively priced product to be produced. Since the commencement of this project, the price of PVC has been increasing and this has in turn led to this material becoming more of an attractive prospect (Mantle, 2007).

It is also essential to establish what will happen with the material at end-of-life. It was suggested that this material would potentially be biodegradable. However, this has not been extensively proven and is still under investigation. The other potential options at end-of-life for this material may be chemical or mechanical recycling, although this may prove difficult for this type of material. The full life cycle analysis of the final product would have to consider these options.
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Appendix B

*Paper Accepted for Publication to the Journal of Industrial Crops and Products*
“Towards Sustainable Flooring Systems:
An Investigation of Novel Materials”

Submitted for the award of The Degree of Doctor of Engineering (EngD)

Portfolio: Volume Two

01.10.03 - 01.10.07

Ms Dianne Tracy Carter, University of Surrey

Industrial Supervisors: Mr N. Stansfield and
Mr J.R. Mantle, InterfaceFLOR

Academic Supervisors: Prof. C.M. France and
Prof. P.A. Smith, University of Surrey
Volume 2: 6- Monthly Reports

Preface

This volume of the portfolio contains the 6-monthly reports compiled as part of this EngD project. The reader’s attention is drawn to the statement made in the Executive Summary:

“It is suggested that it is unnecessary that the reader will need to read the reports in full detail in order to understand the research aims and objectives. The research findings and necessary accompanying detail are all contained in volume one.”
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### Abstract

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2. **Continued Work**

**2. An Investigation into Flow Problems Associated with Tile Backing Filler Material**

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2.2 **Review of Processing**

2.3 **Analysis of the Individual Parts of the Process**

2.3.1 **Bunker Dimensions**

2.3.2 **Investigation of Agitation within Storage Bunker**

2.3.3 **Batch Size/Mass in Bunker**

2.3.4 **Hold Time**

2.3.5 **Performance of Modified System**

2.4 **Introduction of Alternative Limestone Supply**

2.4.1 **Background and Scope**

**4.2.2 An Investigation into the Material Properties of the Current Backing Filler Material**

**4.3 Analysis of Recycled Materials under Consideration as Replacement Backing Filler**

**5 Further Work**

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**12-Month Report, 01.04.04 - 01.10.04**

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1.1 **6-Month Report**

1.2 **Continued Work**

**2. An Investigation Into Flow Problems Associated with Tile Backing Filler Material**

2.1 **Introduction**

2.2 **Review of Processing**

2.3 **Analysis of the Individual Parts of the Process**

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Dianne Carter

6-Month Report

01.10.03 - 01.04.04

“Towards Sustainable Design and Manufacture of Textile Flooring Products”
Abstract

"The EngD research project will be to develop innovative materials and flooring to migrate the textile flooring products towards the company's vision of sustainability. This will involve a holistic consideration of the supply chain from sourcing renewable raw materials, improving/re-engineering production processes, refurbishment, recycling, downcycling and disposal.

The initial project will be to undertake a feasibility study to investigate the technical/market opportunities open to the company including benchmarking against competitors in the flooring market."

This report describes the preliminary investigation into developing innovative flooring solutions. This project is based at Interface Europe, Shelf Mills, which currently manufactures carpet tiles. Its aim is to move flooring through the next paradigm shift to industrial ecology.

The initial part of the project is to examine the industry at present. The early literature review looks at current products in the market place and their perceived benefits and disadvantages. The current manufacturing methods are reviewed in order to fully understand the way in which the industry has developed.

The history of Interface Europe is discussed in order to understand the driving force for change within the industry and the changes that are required. The structure of corporate Interface is also discussed in order to understand the author's position and the way in which new products may be bought about and tested.

Material that is currently in use as flooring components is reviewed in conjunction with consideration of possible natural alternatives. These will be discussed further in the yearly report as part of a fuller literature review.

A further part of this initial investigation focuses on some of the process problems exhibited by the current material and the problems associated with introducing a replacement backing filler for the tile. This investigation is ongoing and will continue through the next six-monthly report.
Background

1.1 History

Historically the human race has set about developing itself by exploiting the Earth and taking no heed of the finite resources available to it. Indeed, it probably never occurred to the industrial revolutionists like Brunel that one day we would be looking at a future where these resources are becoming evermore scarce and at a premium. It was simply a case where if these things were available, then they could be used.

It could be suggested that this was inherited from the early farming systems, where the land was plundered and yet it would always grow back- be it trees, plants or water. However, there was an inherent system of management associated with these traditional fields, e.g. coppicing, would ensure that these were always available for the next year. It seems that the human race cannot continue to rape the Earth and expect it to recover ad infinitum without some system of overall management.

When it comes to animal and mineral management, the human race has an appalling track record. It can hunt animals that it knows to be on the edge to distinction and mine all it can from the Earth without a thought to how these things were formed over millions of years. Yet the industrial world takes just a few generations to ‘revolutionise’ itself and destroy that which was available in plentiful numbers. We have a ‘once in a billion year blow-out sale’ of hydrocarbons.

The first world steals from its neighbours and children as no heed is given to the concept of inter and intra-generational equity; the idea that every person alive on this planet, and those who will come to be on this planet has an equal right to the planet’s resources. The first world tells its neighbours in the third world that they have no entitlement to develop in the way it has and does not share its technologies, when in fact it should be steering our innovation in that direction.

The first world should be teaching its neighbours and children what has been learned through past mistakes. David Oakey is a designer who perceptively comments on the changes that have taken place as we un-learned what was known about nature (Oakey, 2004):

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"My first contact with the carpet industry was in a small town called Kidderminster, which specialized in carpet design and manufacture. My father often retrieved the waste wool from the carpet manufacturers there, to lay as fertilizer on his fields. The colours were blue, pink and purple — it was the late 1950's-60's, a fun and colourful time. Today, I realize that the designers and manufacturers made a terrible error.

A few years later, I noticed that there was no array of colours in the fields and I asked my dad why he didn't get the waste wool anymore. He explained to me that they had made changes to the carpet; ‘They added nylon to the wool and a chemical to kill the moths, so I can't use it for fertilizer,' he said.

Today, I realize that the designers and manufacturers made a terrible error. They neglected to think about how the changes they made to the 100% wool would affect the products after their use. As a designer of interior products, I must constantly be concerned about product life cycles, i.e. what happens after the ‘death’ of a product."

In 1992 at the Rio Earth Summit the terminology of sustainable consumption entered the political discourse and the debate began to be expanded. There is a significant need to reduce greenhouse gas emissions by the domestic government target of 20% in order to reach climate change targets by 2010.

Corporate social responsibility is also being brought to the forefront and can be regarded as "a concept whereby companies integrate social and environmental concerns in their business operations and their interaction with their stakeholders on a voluntary basis" (European Commission, 2002).

There is therefore a developing need for corporations to be responsible for this paradigm shift that is required towards industrial ecology. "Humanity has the ability to make development sustainable- to ensure that it meets the needs of the present without compromising the ability of future generations to meet their own needs" (World Commission, 1987). Since society has developed to be driven by industry, then industry must provide the driving force that is now required.

This vision for the future requires planning and leadership. The industrial world needs some guidance to follow this vision. Legislation and regulation by governments go some way towards achieving this goal. But industry still requires guidance from figureheads within industry who can lead by example.

It may be that we get our blueprint from nature itself as described by Janine Benyus in her book (Benyus, 1997):
"Biomimicry is the process of learning from and then emulating life’s genius. After 3.8 billion years, life knows what works and what lasts here on Earth. Mimicking these designs and strategies, ‘recipes’, could change the way we grow food, harvest solar energy, run our businesses, even the way we make materials."

If the industrial world can replicate nature’s blueprint, it can begin to change how industry works and begin to redesign commerce. Industrial processes can be managed so that the waste from one process is the feedstock for another, mimicking nature’s processes. This course of action will not be easy, as first we need to address what occurs in each industry, starting with our own. Then we can begin to realise how we can change this.

1.2 The Carpet Industry

A majority of industrial processes still work on a take-make-waste scenario. The carpet industry traditionally follows this and manufactures a product that is seen by the consumer in their typical day a multitude of times. It is rare that a consumer will get down on their hands and knees and see what this provision is made from and how it will affect their future.

In fact the carpet industry is huge and worldwide was worth around US$25 billion at the mill level annually (CRI Sustainability, 2001). This massive industry takes a large amount of energy to take raw materials and make them into the final product that the consumer sees and then is disposed of.

Carpet making is an extremely energy-intensive industry and the majority of components in the product are petrochemical in origin, which means that there is a large amount of embodied energy in the product. These constituents have become preferred over the years as they produce the performance required but at decreasing cost as the plastics industry has grown.

In 1995 Interface Inc. sold $802 million worth of carpets, textiles, chemicals, and architectural flooring. In order to achieve this, the company along with the suppliers extracted 2.69 million tonnes of materials from the Earth's stored natural capital. Of this, 880,000 tonnes was relatively abundant inorganic materials, mostly mined from the Earth's crust and 1.76 million tonnes were petrochemicals. Roughly two-thirds of these petrochemicals were burnt up in order to convert the remaining third and the inorganic material into products. (Anderson, MCC, 1997)

In order to consider how to change the industry that is studied, a thorough examination must first be made of the way in which that industry works. As part of this for carpet manufacturing, the method of manufacture must principally be examined and understood.
A carpet will be essentially composed of face yarn, primary backing, a bonding compound and often a secondary backing.

Figure 1.2.1 Typical cut pile carpet profile

There are many types of face yarn with many methods of construction in the carpet industry. The most common are shown in the figures below.

Figure 1.2.2 Carpet manufacturing by square metres (The Carpet Primer, 2003)
Nylon is used in a large percentage of carpet applications as it offers low cost, good wearability and abrasion. If it is solution-dyed then it is generally resistant to the harsh chemicals used in industrial cleaning treatments and is good for hard-wearing applications.

Olefin (polypropylene) offers an excellent water-vapour barrier and so is easily cleaned. It again offers good wear-resistance because the colour is added to the fibres during production and is inherent across the entire fibre.

Polyester offers a luxurious feel and so is used in thick-cut pile textures. Wool offers similar properties, but because of its historical significance it is known as a luxury material. Both are generally soft to the touch, but require a high bulk fibre density in order to achieve good wear properties (CRI Primer, 2003).

The dyeing method will also have an impact on the wear resistance of the material as during quality assessment the colour change after wearing is noted. If the fibre is coloured throughout, cutting the fibre perpendicular to its direction will have no affect on the colour change. However, if the fibre has not been dyed throughout (for example in some of the inferior versions of traditional dyeing methods), then the colour will appear to have faded. For example:
Figure 1.2.4 Solution dyed and tradition method compared after wear - note apparent loss of colour

The wear and associated properties of the carpet will also be affected by the method of manufacturing. It has been shown that in the US the majority of carpet is manufactured by tufting - using mostly nylon yarns.

Figure 1.2.5 Illustration of tufted carpet (Brintons, 2003)

Higher priced wool/nylon blends are also produced by this method, although the nylon yarns, in particular the continuous filament nylon, predominate the tufted market.

Tufted carpet styles range from loop, cut pile, and combinations of cut and loop. They often offer different pile heights across the carpet that results in different patterns within the carpet, as different colour threads can be made prominent. Stepping or zigzagging using individual needle bars is used to achieve this.
The pattern of a tufted carpet is generally restricted by these methods unless secondary dyeing methods are used after the carpet is constructed. Traditional woven carpet is produced in smaller quantities and offers a greater amount of variety. Axminster and Wilton are some of the better known woven carpets produced in the UK. The principle of the carpet making is that the pile yarns and the backing yarns are interlocked and this method has changed little in the last 200 years.

In an Axminster carpet weave cut tufts of yarn are inserted at the point of weaving by means of grippers. The appropriate coloured ends of the yarns are selected by jacquard mechanisms and presented to the grippers before the tufts are cut from the yarn. This means that during the manufacturing process a larger variety of colours can be utilised, although at the expense of greater energy considerations.

![Figure 1.2.6 Woven Axminster (Gripper) (Brintons, 2003)](image)

Woven carpet will absorb considerable stresses and strains in use since the backing cannot delaminate, as it is an integral part of the whole carpet. The whole carpet is three-dimensional and up to twelve backing yarns supports each individual tuft. The history and manufacture of this type of carpet consequently means that it has gained a reputation for resilience and luxury.

Needle punched or needle felt carpet has developed as a result of the need for more versatile materials and cost reduction. A web is laid lengthwise, crosswise or diagonally on the needle machine at the same time as fibrous material is poured on top in various colours. The needles punch the yarn through the backing and the tufts are formed. This process can be repeated a number of times in order to build up the pile weight in the carpet. The resulting material is then anchored using a latex binder, compressed and levelled on a press or calendar.
Fusion bonded carpet is produced by implanting loops or yarns directly onto an adhesive coated backing. The yarns are not stitched into the primary backing before the adhesive is applied and may be cut before or after application.

Fusion bonded products are often printed after construction for specific patterns. The pattern is sprayed on, rather like the manner of an ink-jet printer so the designs are very detailed and can be very exact. The print is set using steam and then cooled and washed off to complete the design.

There are a number of systems available for backing carpet before cutting into carpet tiles. Two main methods of backing the carpet tile at Shelf Mills are used. They are known as Graphlex and Glasbac. They are both versatile enough to be fitted quickly with minimal floor surface preparation.

The Graphlex backing is a patented system that is a carbon polymerised composite incorporating layers of fibreglass. The fibreglass is multidirectional and therefore its main purpose is to offer dimensional stability. It is desirable that the backing system be relatively heavy so that it will not warp, wrinkle or dome under heavy traffic or extreme changes in humidity and temperature.

The result is a backing that contains, by weight, 3% fibreglass, 1-2% fleece and over 95% bitumen mix (33% pre-modified bitumen, 67% limestone). The bitumen is applied hot and cooled to allow it to set.

*Figure 1.2.7 Needle felt carpet*
The Glascabin system is a thermoplastic composite that again incorporates fibreglass for dimensional stability. The difference is that instead of bitumen as the primary filler, PVC is used.

The backing system is ‘punched through’ with a conducting paint in order to reduce static build-up in use, which makes the product suitable for electronic environments. This patented system is known as ‘ComputerGuard’.

Other options for backing include the addition of magnetic strips that make the tiles particularly suited to the Intercool system of raised flooring which allows easy access to under-floor cabling. The whole backing system may also be magnetised so that the tile can be cut and placed at any point and this is known as ‘Magbac’.
There are literally thousands of permutations of backing system and facelcloth that may be ordered by the customer such as ReCushion Bac, System Six, Unitary and Springbac. This means that the customer has full flexibility when choosing face cloth and backing system for their particular requirement.

The tiles are precisely cut so that they may be laid with a broadloom effect. The tile cutting leads to waste at the end of the manufacturing process as they are cut from two metre wide rolls. This is known as ‘window waste’ and comprises a large amount of the waste generated on-site that is not currently recycled.

There is a large amount of mechanical manipulation of the constituents and heating and cooling cycles that utilise a large amount of energy and it may be possible to remove from the process. Each means of manufacture uses these methods and there may be a way that the environmental impact could be reduced. This will be studied further as the project progresses.

1.3 Environmental Concerns

Each process in the carpet making relies on a large input of energy and raw materials. Often, the backing material is made from natural or recycled materials such as jute, but generally the main constituents are all petrochemical based. This has only been the case since 1954, when up to that time cotton was the only fibre used in tufted products (CRI, History, 2004).

Most carpet is not worn out in its lifetime and is replaced for other reasons, such as the colour becoming outdated, redecorating, or the carpet becomes discoloured. 70% of carpet is discarded for these reasons and so could be re-dyed to extend its lifetime in service (Color Your Carpet, 2001). In the US annually 800 million square yards of carpet are land filled, of which little can be recycled easily (Weiss, 2003). However, down cycling is often used, as previous carpet becomes the filler for a new carpet backing. Incineration is an option that may recover some of the intrinsic energy in the product, but is often not a socially acceptable alternative (Duchin, 1998).
The carpet industry has been taking steps in recent years in order to reduce its impact on the environment with the signing of the Memorandum of Understanding for Carpet Stewardship (MOU). This voluntary agreement was signed by members of the carpet industry and US government aiming to eliminate landfill disposal and incineration of used carpet. These initiatives have resulted in the US carpet industry reducing energy consumption equivalent to parking 226,000 cars in one year (CRI Sustainability, 2001).

Collins and Aikman (U.S. Patent) operate a production-scale operation that claims to be able to recycle any vinyl-backed carpet 100% into a 100% recyclable product. The finished carpet contains a minimum recycled content of 30% overall. This however leaves 70% that is still virgin material and the associated energy impacts.

Interface has introduced Glasbac:RE which is manufactured using post consumer recycled PVC. Re:Entry is another innovative solution that involves reclaiming carpet, renovating and repurposed for donation to schools, libraries, churches, shelter groups, missions and other non-profit organizations. These are some of the first steps towards producing an entirely sustainable product within carpet manufacturing.

The Interface Sustainability Report of 1997 showed that there were many advances made in the company during the period from 1994, but yet the take-make-waste open system was still prevalent. The raw material input to make 554 thousand tonnes of carpet tiles worldwide involved over 97 thousand tonnes of face fibre, 22 thousand tonnes of backing material, 500 thousand tonnes of chemicals and 28 thousand tonnes of auxiliary materials, including packaging and office supplies.

The majority of energy input to the product is in embodied energy in the material ($7.4 \times 10^{12}$ BTUs) compared to the energy required to make the product ($0.6 \times 10^{12}$ BTUs). Interface considers a holistic approach to sustainability with the result that many manufacturing advances are taking place, including energy and water conservation, reduction of hazardous materials in use, waste reduction by improvement of handling procedures, packaging, shipping and storage, decreased landfill use and the 100% use of renewable energy at all U.K. sites. Since the QUEST initiative has been in place (Quality Utilizing Employees Suggestions and Teamwork), in conjunction with the Ecosense initiative there has been a 40% reduction in waste across the board.
QUEST is the waste reduction programme initiated in 1995, which allows employees to make suggestions to improve the efficiencies of manufacturing and office procedures to reduce waste. Interface developed the EcoSense Points System to educate associates about sustainability and help them discover things they can do to work to become sustainable. Interface awards EcoSense Points for the successful completion of activities that fall into categories of environmental management systems, quality management systems, sustainability training, sensitivity hook-up, employee safety and education, resource efficient transportation, EcoMetrics, purchasing and Eco-Efficiency.

It is all very well introducing recycling bins in every office, saving energy and water in processing and recycling cans in the staff canteen, but as Paul Hawken so astutely observes in his book The Ecology of Commerce; “It’s like trying to bail out the Titanic with teaspoons” (Hawken, 1993). So, fundamentally, industry needs to change its business practices and commerce must be redesigned if the major environmental disaster awaiting the human race can be averted.

The smaller approaches have not fundamentally changed the processes that occur in every factory, although they have changed the underlying principles. Although petrochemicals and materials are still converted to product, the process is more refined and less wasteful. It is one last transition that needs to take place towards industrial ecology and the company is aware of the urgency of this need.

Research and Development in the United States is currently looking at alternative sources for the materials that make up a carpet tile and thus migrate the product in a more sustainable direction. Interface, Inc. has already introduced in America and Europe a carpet tile with fibres made from polylactic acid derived from corn, which is a first attempt at a sustainable product. Whether it is one that the consumer will buy is yet to be proved.

Interfaces vision perfectly sums up their plan for the future:

“To be the first company that, by it’s deeds, shows the entire industrial world that sustainability is in all it’s dimensions: people, process, product, place and profits- by 2020- and in doing so we will become restorative through the power of influence.”
1.4 Project Aims and Structure of This Report

This project will provide flooring solutions that will migrate the entire product towards the company's vision of sustainability, whilst also considering customer viewpoint, resulting in an increased customer perception and consequently customer loyalty. This will involve holistic consideration of the supply chain from sourcing renewable raw materials, improving/re-engineering production processes, refurbishment, recycling, downcycling and disposal.

The project can be broken down into four sectors: refinement of current manufacturing processes, new processes, use of more sustainable materials and flooring management. This gives four clear paths for the project to take. Initially all paths will be considered, with a view to specialising in one particular area.

The carpet manufacturing process is initially studied in great detail, which is included in the preliminary critique. This report also includes current steps being taken to improve the manufacturing process and research being undertaken on-site. In addition this report focuses on the alternative materials that may be considered for other flooring and textile solutions.

Interface's holistic approach to sustainability has resulted in many manufacturing advances, including energy and water conservation, reduction of hazardous materials in use, waste reduction by improvement of handling procedures, packaging, shipping and storage, decreased landfill use and the 100% use of renewable energy at the Shelf Mills and Craigavon.

However, the customer, from a simplistic point of view, rarely considers this approach. They will consider recycled material or recyclable material of a greater benefit to the environment than these approaches (although in actual fact more energy may be used). Customer perception must be considered from a marketing point of view as there is also the discernment that products with a greater amount of recycled content are inferior to those made from virgin materials.

These perceptions will be questioned at consumer and expert focus groups. Social research will be an important part of the project development, as product perception would lead to saleability. This process needs to be fully understood in order to consider how the market may receive future products.

Greater understanding of the needs of flooring solutions will be achieved with a view to create a more sustainable flooring product. In order to achieve this, the current manufacturing process and project management need to be first examined and understood.
2 Interface Europe

2.1 Interface Manufacturing

In order to understand how Interface will develop in the future, an understanding must first be developed of its history. It is this history and the experiences of the founder, Ray Anderson, that are driving the company now, towards the vision of sustainability.

In 1973 Ray Anderson founded Interface as Carpets International Georgia. His vision was to use his 14-plus years of experience in the carpet industry to adapt European technology to produce free-lay carpet tiles in America. This was in partnership with Carpets International Plc, based in the UK. In 1982 Ray bought out his share of the company and renamed it Interface, Inc. after the Carpets International Plc was taken over.

The reason that Interface chooses to manufacture modular flooring and not broadloom is that most of the wear of a floor only occurs in 20% of the surface and so modular flooring means that this section can be selectively replaced—offering savings on cost and material (Interface, Why Modular, 2003). It is also easy to replace these sections as Interface have developed their ‘Renovations’ system that lifts furniture and keeps it in place. This system means that the floor can be installed with minimal disruption to electrical connections, furniture assembly and no downtime.

Modular installations are also much faster that conventional carpet, typically saving 50% on man-hours. This is because there is no underlay required, no seaming or dye lot mismatches. If a specific design is required, with modular tiles there is the flexibility to add larger patterns and expand aesthetic possibilities. It offers the customer some creative freedom and design flexibility.

After becoming such a major force in the flooring industry during the seventies and eighties with little regard to environmental impact, bar that which was required by legislation, Interface found itself in a position that had become briefly incomparable. The company was enjoying the economic boom of the era and had acquired a number of flooring businesses in the retail and office sector as the businesses grew together.
During 1984 the industry hit a brick wall with the collapse of new office construction in the United States and so the company diversified into office renovations and healthcare. Once again, in 1991-1993 markets began to change with the downsizing and re-organisation of companies as well as that of Interface, Inc. With new management structure in place, Ray Anderson - Founder, Chairman and CEO of the billion-dollar company, found himself questioning his role and made some fundamental changes to the philosophy of the company, resulting in the 2020 vision (Anderson, MCC, 1998).

Interface has a 40% market share in carpet tiles and over 1 billion dollars in sales every year. They have 29 manufacturing sites across four continents, with sales and manufacturing in over 30 countries, selling to more than 110 countries worldwide. They directly employ over 6,000 people across the globe (Interface website, 2004).

Interface is the world’s leading commercial carpet and interior fabrics manufacturer. Its corporate headquarters are based in Atlanta, Georgia with its founder Ray Anderson remaining in the role of chairperson, and Dan Hendrix as president and CEO.

Interface Research Corporation (IRC), based in the US, is intended to provide basic research and technical support to all the Interface subsidiaries worldwide, provide leadership in the development of socially sustainable practices and develop newer and more environmentally friendly technologies, processes and products towards the goal of sustainability. IRC provides more long-term research in the field with three laboratories and a materials science pilot plant (Interface website, 2004).

The Europe/Asia/Pacific main offices are based at The Shelf Mills, Halifax, West Yorkshire. The company has a very hierarchical structure with linear chains of responsibility and accountability. There are sales and marketing activities in the majority of these regions.

The major manufacturing sites in Europe are based at Scherpenzeel in Holland and Shelf Mills. Both sites have associated subsidiary functions such as engineering, materials research, quality control and quality assurance.

Scherpenzeel produces mainly large volumes of the Heuga branded product whereas Shelf Mills produces much smaller volumes of the Interface branded products. This results in differing needs and purposes at each site as the Heuga brand is less expensive and offers better value for money. This results in a bigger domestic market proportionately than the Interface brand.
Both sites produce mainly modular carpet (or carpet tiles), which has the feel and durability of a traditional carpet, whilst offering additional benefits of flexibility. The carpet tile produced is 50cm x 50cm and offers a multitude of designs and textures.

The facecloth can be imported from Craigavon, Northern Ireland on rolls and backing lines complete the product at Shelf Mills. Fusion-bonded product is produced and backed on-site.

Interface is now urgently searching for a replacement backing system that may involve more renewable materials or recycled content. As a first step, since it constitutes a major part of the Graphlex backing system by weight, is to examine the limestone component. It may be feasible to use post-industrial recycled filler as an alternative and this is discussed later in this report.

### 2.2 Process Materials Research

The European technical director has responsibility for technical sales support and testing, health and safety, systems audit development, engineering and development, quality control and assurance and accreditation. It is his role to co-ordinate the Process Materials Research (PMR) issues between the two sites in Europe and relates these back to the activities of the IRC in the US.

The PMR function is to provide short-term solutions to today’s problems. There are PMR functions at the major manufacturing sites to provide support to the manufacturing processes and engineering team.

A fast return is usually required which means that there are fewer resources available for medium-long term thinking. This project aims to fulfil some of these medium-long term projects that have been generated and may help to provide solutions to the longer-term problem. These projects are generated in-house and this process needs to be fully understood in order to be able to operate within these confines.

A work instruction currently defines the way that projects may arise and responsible Project Initiation (Interface Europe, QMS, 2002). The inputs leading to the initiation of a PMR project can be from a number of areas within or outside the Company. These can include: requests by customers or sales and marketing functions, recognition of a need to investigate and correct a particular quality fault, the availability of new materials with enhanced performance or the implementation of Company policy.
The PMR Manager or the Technical Director will consider the desirability of initiating a specific new project. Where a new project is felt to be desirable, the PMR Manager shall create a PMR Project Application. This would be discussed with the Technical Director to confirm approval.

The PMR Manager would set the objectives for the project, select a project leader and wider team, if appropriate, and agree the research process to be followed with the project Leader. The reporting and review requirements and proposed timing shall also be determined at this stage. This information is then recorded on the Project Application and becomes the documented Project Definition.

Day to day planning of project work is be carried out by the Project Leader and is consistent with the priorities agreed with the Process & Materials Research Manager at project initiation.

Currently PMR projects require approval by the Technical Director and will follow the subsequent flow-chart.
A trial run will produce the carpet in large quantities and in different colourways. The product will then be rigorously tested following the standard procedures and approved if it meets these standards. The test procedures are as follows:
Each new product under development is rigorously tested in order that it can be sold to the customer under detailed specifications. The customer has specific requirements and needs to be able to pass these on to their customer. Each product produced by Interface is quality controlled and assured in this way.
2.3 Testing Procedures

Any new product that may arise as part of this project will need to pass stringent quality control measures. These are described in detail in this section in order to begin to understand the material properties that may have to be considered in an alternative product. These tests take place as part of quality assurance on a daily basis for every product produced. These testing procedures are taken from the British Standards that include colourfastness, fibre bind, Hexapod tumbler, Vettermann drum and castor chair test.

British Standard BS EN 1307:1997 describes the general classification and testing carpet. Each test is designed to simulate what may happen to the carpet in use. For example there is included colourfastness- to light, rubbing wet and dry, fibre integrity and fibre bind for synthetic carpets. Each test results in a classification that may be given to the carpet to indicate its quality.

The castor chair test is described in BS EN 985:1995 and is again designed to simulate conditions in use. The carpet is simply mounted on a rotating circular test platform of 800mm diameter. Castors are set on an assembly arranged at 120° intervals and are free to rotate around the 130mm diameter. The castors rotate at 50min⁻¹ and the platform at 19min⁻¹. There will be a suction device to remove any resultant debris.

![Figure 2.3.1 Castor Chair Test (British Standard EN 905:1994)](image-url)
The whole assembly revolves for a set amount of revolutions, depending on the test, and then the carpets appearance is assessed.
British Standard BS ISO 10361:2000 describes the Vetterman drum and hexapod tumbler tests. They both work on the same principle of simulating the conditions of use. The Vetterman drum is a larger apparatus that revolves with a steel ball inside with rubber feet that fatigues the carpet, which is lining the inside of the drum. A circular brush constantly removes broken fibres.

Figure 2.3.4 Figure showing Vetterman drum test (British Standard ISO 10361:2000)

Figure 2.3.5 Figure showing steel ball used in Vetterman drum test (British Standard ISO 10361:2000)
Figure 2.3.6 Photograph showing Vetterman drum test on-site

A set amount of revolutions occurs (22,000 for heavy wear, 5,000 for early changes in appearance) and the carpet is removed and examined.

A similar method is used for the hexapod test, but with different dimensions. The carpet is also vacuumed during and after the test to remove excess fibres. A total of 14,000 revolutions are used to simulate heavy-wear and 6,000 revolutions to simulate early changes in appearance or use in less severe sites.

Figure 2.3.7 Hexapod (British Standard ISO 10361:2000)

Key
1 Polythene stud
Figure 2.3.8 Hexapod tumbler cross-section (British Standard ISO 10361:2000)

Figure 2.3.9 Photograph of hexapod tumbler lined with carpet

Each standard test used in the carpet industry is designed to reproduce conditions in use and repeat them over a number of cycles to simulate an amount of time in use. These tests are designed and reviewed by those in the carpet industry on a regular basis.

Appearance assessment is also standardised, as this is the method by which the carpet properties are categorised. These can be found in BS EN 1471:1997 describing the carpet being assessed with reference to a set of standards. These standards can be found at the British Textile Technology Group (BTTG) in Leeds.
The drawback with these types of tests is that they do not get to the primary principles behind the fracture of the fibres. If we were to look closely at the method of failure of the facecloth were to be examined it may be that fundamental parameters could be defined that a material may have in order to pass the heavy-duty characterisation. This would lead us on to testing materials at an earlier stage before trials need to be run.

As a further part of this investigation a visit to BTTG will be undertaken to examine the standard testing procedures. Simulation of the type of fibre fracture may be considered as a larger part of this project arising from the testing methods, in conjunction with consideration of new materials and dematerialisation.
3 Materials

3.1 Dematerialisation

As part of the environmental issues that have been raised so far it has been noted that each element of the carpet tile performs a function. There are two ways that become apparent of reducing the environmental impact of the tile. The first is to reduce the amount of material in the tile, whilst retaining the same materials. The second is to change the materials to those that are sourced from natural elements, recycled or recycleable whilst retaining function, which will be discussed in 3.2.

If the material components of a carpet tile are considered, then each element offers an individual characteristic. The carpet tile could be broken down, with what each component offers considered and consequently a reflection of how the content may be reduced may be performed.

The face yarn provides the design and quality that the customer feels. It can be used to exhibit logos, to express a particular style or mood. The face yarn tends to provide the emotional attachment that people may feel in their room. It is the most important part of the carpet tile as it is this part that the customer will be in touch with on a daily basis.

The face yarn would have to be chemically stable, resistant to sunlight, able to withstand harsh cleaning chemicals, colourfast but versatile in coloration possibilities. It has to be durable and wear-resistant for a good lifetime, but be ductile and not feel harsh.

Face yarn should offer good colour clarity and so may scatter light in order to reduce the appearance of stains. It ought to provide low levels of static generation in an age where electrical equipment is prevalent.

The backing fabric is added to provide dimensional stability whereby it is strong and stiff. It is also a barrier to moisture to protect the under-floor. The backing material also adds bulk to the carpet tile so that it can be laid easily and remains in place. The adhesive could be removed or altered if the backing material is changed.

In order for dematerialisation to take place the replacement option must therefore include all of the stated features. Carpet tiles have already reduced the total amount of material required to operate as a flooring solution, whilst still functioning in the same manner as a traditional carpet, as discussed in section 2.1. This is a first step towards dematerialisation as the total material required to perform the same role is reduced.
Carpet tiles already offer an advantage over the traditional broadloom carpet as in fitting there is a great deal less waste. Modular carpet installation typically produces around 67% less waste than broadloom carpet (Interface, Why Modular, 2003), which means both cost and material savings as more of the flooring ends up in the floor and less in landfill. Changing the flooring is also easy and the patterns can quickly adapt to changing styles.

The tiles can be easily cut to size to fit any shaped room and areas that suffer more traffic and wear can be selectively replaced. By changing the tiles on a regular basis, the pattern could be subtly changed to give an altered appearance.

It is particularly useful to have carpet tiles in a child’s room as brightly coloured tiles can be used to create a pattern that may be changed depending on wear, spillages and design. Shapes can be cut from the tiles to include favourite pictures, even after laying. These all assist the dematerialisation of the carpet, as less is needed for any given wear time.

A breakthrough carpet tile has been developed at Interface based on the concept of biomimicry- the idea that natural systems can guide the design of man-made products as described by Janine Benyus. Entropy is laid randomly and provides near-zero installation waste, as there will be few spare tiles. The Entropy range also extends the lifecycle of an installation, as the tiles can be interchanged when the wear rates of different traffic areas diverge.

Another method of reducing the material used for a flooring solution over a given period is the idea of the ‘Evergreen Lease’. The concept is that a customer leases a flooring solution from the business, rather than buying it. The services that the carpet provides are sold instead, i.e. the colour, design, texture, warmth, acoustics, comfort under foot, cleanliness, and improved indoor air quality, but not the carpet itself. The customer pays monthly for these services and therefore the paradigm shift is achieved towards dematerialisation (Anderson, MCC, 1997).

The business would take back the flooring and either re-use or recycle the material. Re-using involves cleaning the tiles thoroughly and may involve re-dyeing the surface yarn to keep in with current fashion trends. The backing may also need to be renovated in order to restore the impact resistance of the flooring. These Re:Entry products are currently donated to non-profit organisations (Interface website, 2004).
Re-cycling is currently more energy-intensive than re-use and is therefore less desirable (Krivtsov, 2004). However, if the carpet has deteriorated too far then the only option may be to reduce the flooring to its constituents. In this case it is more desirable to consider a floor covering that would be 'un-zippable' and could be broken down easily. In this case the individual elements would be recycled separately.

3.2 Natural Materials

There are many small companies that offer a variety of floor coverings that contain a quantity of natural materials. The materials most often included are jute, hemp, fiscal, cotton, wood, silk, linen, bagasse and more (Geosites, 2003). A brief overview of these materials is described below, but each material should be considered as to how it fits the criteria described for each part of the tile. Further details are sourced here from the Department of Trade and Industry Manufacturing Advisory Service (DTI, 2003).

Natural fibres are either extracted from the leaf, the inner bark, fruit or seed, animal wool or hair, insect cocoon or mineral product. Fibres are used to form into threads, yarns and ropes that may be woven into tapes or fabrics. The drawback with natural fibres produced in this manner is that they often vary in properties from crop to crop and depend on seasonal variations.

Hemp is a material that is having a great deal of attention drawn to it in recent times. It can be a cheap crop that can be utilised in a number of ways for example its seeds can be made into nutritious food bars and can be processed in the same way as soya products. The fibres produced from the stem are extremely tough and are already used in carpets, reinforced panels for cars and other applications (Manitoba AFR, 2000).

Flax is produced from the inner bark bast fibre from the flax plant. It has a high specific stiffness that may make it suitable for use as a dimensional stabiliser in the backing if the fibres are laid down multidirectional. The tensile strength is high at around 800MPa and it absorbs little moisture. It is currently used to make paper for cigarettes, linen and paper.

Manila hemp (abaca) is produced from the leaf of the *Musa Textilis* tree. It has a high tensile strength of around 900MPa and a high specific stiffness, which means that it offers good abrasion resistance. It is resistant to mould and rot and so consequently finds itself in applications such as marine cordage, abrasive packing papers and teabags.
Sisal is made from the leaves of the sisal tree and is already found in luxury carpets and high strength papers. It has a medium-high strength of around 600MPa. It is hardwearing but expensive.

Seagrass is used in carpets and rugs as well as roof thatching in coastal areas. This is another advantage that natural materials may offer if they are grown in the areas that they are utilized. This saves on transport and thus reduces an important environmental impact. Seagrass offers good sound and thermal insulation and therefore reduces heating needs in the home, which in turn reduces a further environmental impact. It is relatively cheap and non-flammable.

Cotton from seed is one of the most widely used fibres in the world today in a variety of applications- mostly clothing and paper. It is durable, but with a low tensile strength and can absorb a large amount of water.

Coconuts have also come to prevalence in recent years as they offer a use for every part. The flesh and milk can be eaten (or in young coconuts used for emergency plasma transfusions), the fibres and hair from the husk can be used in carpets and door mats or as fibrous fillers. They are highly rot resistant and have a strain-to-failure of about 20%. They offer low stiffness and tensile strength (220MPa), so they could be considered for replacement of polymers in some situations.

Animals can also provide hair and hide that is used in a number of current applications. Most of these are for clothing or luxury carpets. These applications emerge as the hair is soft, lightweight, durable and offers good thermal insulation. Depending on the animal type, the hair may or may not absorb water easily. There are hundreds of different breeds of sheep, camels, goats, llamas and other exotics that provide hundreds of different types of hair/wool.

Hide or skin can also be taken from any animal and its properties depend mostly on the area and type of animal it is take from. Treatment can alter the properties of the resultant material and its uses. Leather is used mostly in the clothing and upholstery industries.

Silkworm cocoons can be boiled in water to release a single continuous element. The cocoon contains a developing larva, which is destroyed in the process. It is soft and lightweight with excellent wicking properties as it can absorb a great deal of water. It has excellent insulating properties, but its reflective appearance can be dulled easily upon exposure to UV rays. It is used for luxury clothing, thermal clothing and luxury home furnishing.
There are obviously an enormous number of animals and plants available that may be alternatives to the current backing and facecloth systems. It is narrowing this field down that poses the first challenge to the researcher. The first materials to be considered are those that could be produced locally and therefore reduce impacts further.

An addition to the problems caused in selecting a fibre that is animal in origin is that then the animal treatment should be considered. This enters into the social responsibility that the company has to the environment.

As a further part of this research these natural fibres will be analysed further and an investigation into their properties carried out. Continuing from this, the material properties will be assessed against those of the materials currently in use. In order for any component to be replaced by one of lesser environmental impact, the customer must be convinced that the replacement can perform the same function, or better.
4 An investigation Into an Alternative Filler for Tile Backing

4.1 Introduction

There has been a continuing need at the Shelf Mills to introduce a greater recycled content into the backing material. The backing material contributes over 95% by weight of the total tile and if the limestone in the backing were to be replaced by a recycled material, the total recycled product content would be about 65%.

The aim of this project will be to research and investigate existing materials used for backing fillers i.e. calcium carbonate (limestone). Limestone is a sedimentary rock composed of carbonates, namely the minerals calcite (calcium carbonate; CaCO3) and dolomite (calcium magnesium carbonate; CaMg(CO3)2), derived either chemically or organically. This is extracted from the Earth, ground and sieved to obtain the required particle size distribution.

There will be a need to understand the material characteristics based on particle size, morphology, temperature and humidity. Ambient conditions may affect these characteristics and consequently the flow behaviour of the material.

This investigation is divided into two parts. The first is an analysis of the current material and associated flow problems. This takes the form of a preliminary investigation into the material and its characteristics in order to understand the manner in which it is currently transported around the line. If different characteristics are exhibited under different conditions these must also be understood in order to implement process changes.

The second part of the investigation is to examine any replacement fillers in order to ensure that they can be implemented online efficiently.

There are problems with the current material flowing through the line and bottlenecks have been identified in the process. If these problems can be related to material characteristics, then it may be that these could be avoided in replacement filler.

There have been numerous problems with the flow of limestone into the mixer for use in the bitumen backing line. The system appears to have problems flowing from the heated storage bunker (SB56) to the weighted bunker (WB58) during certain times and conditions. The following diagram shows the part of the transportation system that exhibits the perceived bottleneck.
Figure 4.1.1 Line diagram showing perceived bottleneck at bottom of heated storage bunker (SB56)

It is perceived that during summer, conditions are such that the flow problems increase. In the heated storage bunker, the limestone has been heated to around 150°C via the oil-heated screw, which draws material from the colt limestone storage bunker and the external tank D shown in the line diagram below.

Figure 4.1.2 Line diagram showing heated screw (on left) and external tank
It is stored in this bunker until required in the weighted bunker. From here, a dose of approximately 250kg is delivered to the compound mixer (CM28) via the dosing screw at 2.4kg/s.

The mass of material in the weighted bunker is measured using the data point WTA58 and the mass of the material in the heated storage bunker is estimated using a vibrating probe, offset from the centre. The vibrating probe assumes that the level of material is consistent throughout the diameter of the bunker, and that the material is compacted to the same degree throughout. In fact, after successive filling and emptying cycles the material becomes more compact around the circumference of the hopper as often ‘rat-holing’ takes place.

**Figure 4.1.3 Assumptions made by the vibrating probe**

Therefore, inaccuracies may arise during measuring of the material flow and adjustments must be made for this during processing. Line data has shown that the rat-hole collapsing results in a sharp drop in the amount of material measured by this probe.

In order to keep the material flowing through this bunker adequately, pads have been introduced at the entrance to the dosing screw that are designed to aerate the system at low pressure in order to encourage material flow, shown schematically here.

**Figure 4.1.4 Aerator action**
In addition to this system, mechanical means have been introduced, whereby the operator would apply sharp force both inside and outside the bunker to agitate the material and encourage the rat-hole to collapse. This method, although effective, is not ideal since the bunker will eventually become misshapen and the pads become broken. This results in the system not being able to work effectively as it was designed.

It is the intention of the initial enquiry to assess the conditions that cause the most problems with mass flow. If there is the perception that flow rates are different at this bottleneck due to seasonal variations, this will form the first part of the investigation. The atmospheric conditions will be monitored and related to the flow characteristics observed on line.

The current material in use will help to dictate these flow characteristics. If the flow characteristics vary depending on ambient conditions and material properties affect flow characteristics, then ambient conditions may affect material properties.

It is the secondary intention of this enquiry to compare the material properties with the ambient conditions to assess if any changes take place in the material. If samples are taken under different ambient conditions and the material characteristics can be well defined, they may be related back to the conditions that may cause these changes. Consequently, the flow properties may be predicted by atmospheric conditions and ultimately safety measures may be put in place in order to maintain the flow conditions required to maintain the throughput of the line. These recommendations will be an ongoing part of the investigation.

If the backing filler material is to be replaced by an alternative, then the properties of the replacement need to be fully understood. If the line is to run to its full capacity continuously then the new filler needs to cause no problems that cannot be compensated for in the normal day-to-day running of the business.

Particle size and distribution have been previously highlighted as factors that may affect processing. A small amount of particles that are over 250μm had been included as part of the PVC mix, as limestone is also used a filler in this application. However, the PVC applicators use a blade method to apply and then reduce the amount of liquid on the fleece. These larger particles become trapped under the blades and tear-outs have occurred on line.

The method of application on the bitumen line is by a set of rollers. Since they rotate at different speeds and have a set gap between them, the thickness of application can be controlled.
This free-moving system may mean that the larger particles remain behind on the rollers and are not transferred onto the fleece. However, since the limestone replacement will ultimately be used in both the PVC and bitumen mixes then it should conform to both standards.

Particle size and distribution are also important in the way that they affect the viscosity of the mix to be applied to the backing system. It is believed that a large amount (>5%) of fines (<53μm) in the limestone will have an adverse affect on the bitumen mix such that the viscosity becomes too high at the current temperature of application for effective transfer.

It is not advisable to increase the temperature further due to increased energy use and associated costs. It will also result in further energy costs as the backing system will then have to be cooled to room temperature via a refrigeration system. Therefore, a thorough investigation of particle size and distribution is required.

It is the intention of the initial enquiry to assess the conditions that cause mass flow problems and to simulate them under laboratory conditions. This will enable some of the causes of these problems to be identified and eliminated, which would result in increased process efficiency.

This investigation is ongoing and is divided into sections that describe the steps taken in the investigation thus far. Initially the particle size, chemistry and morphology of limestone currently in use as backing filler for carpet tiles were investigated using Scanning Electron Microscopy (SEM) and sieving. SEM is a useful tool for examining particle shape and size and retrieving chemical information.

Samples were taken after varying processes and conditions had been applied to examine if any change in morphology took place and the environmental conditions noted. It was decided that the mass flow problems associated with the limestone could not be attributed to chemistry alone.

At present, the limestone is heated and transported around the site by mechanical processes, before it is mixed with the pre-modified bitumen and used as the backing filler. There is the perception that the flow characteristics are dependent on climatic conditions and seasonal variations. It is the intent of this study to verify or disprove these claims.

As part of this investigation, it would be rational to model the bitumen delivery systems, calculate flow rates and compare with the actual data collected. This will lead to process and product recommendations to achieve the plant requirements of a line speed of 10m/min.
4.2 Assessment of Material Currently in Use

4.2.1 An Investigation into the Relationship between Ambient Conditions and Moisture Content of Sample

In order to assess the perceived problems with the flow of the current material, which were thought to be caused by material differences, samples were taken initially over several days at different times. In order to compare new materials to the standard limestone used as a filler in the backing material, it must first be analysed and documented.

Samples of limestone were taken from the line under various conditions from the site shown by the red arrow. This site was chosen as the vent is easily accessible and it is close to the perceived bottleneck of the system.

Figure 4.2.1 Photograph showing access port for collection of limestone (in reverse to line diagram)
Figure 4.2.2 Line diagram showing access port for collection of limestone

In order to observe if outside ambient conditions may affect the sample, as ambient air is used to aid the transport of material into the factory. The ambient conditions inside the factory may affect the material as several vents are available to the system, as seen in figure 4.1.1 and 4.1.2. The ambient temperatures were noted both inside and outside the factory during sampling and these are shown in Table 4.2.1.

<table>
<thead>
<tr>
<th>Sample Time Taken</th>
<th>Air Temperature Inside (°C)</th>
<th>Air Humidity Inside (%)</th>
<th>Air Temperature Outside (°C)</th>
<th>Air Humidity Outside (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>04/12/03 4pm</td>
<td>30.7</td>
<td>20.2</td>
<td>9.5</td>
<td>81.9</td>
</tr>
<tr>
<td>05/12/03 10am</td>
<td>28.8</td>
<td>19.8</td>
<td>14.9</td>
<td>42.1</td>
</tr>
<tr>
<td>08/12/03 5:30am</td>
<td>16.2</td>
<td>28.9</td>
<td>-0.7</td>
<td>83.5</td>
</tr>
<tr>
<td>08/12/03 7:45am</td>
<td>20.3</td>
<td>23.9</td>
<td>-0.9</td>
<td>81.9</td>
</tr>
</tbody>
</table>

Table 4.2.1 Sample Information

The samples were taken at approximately 130°C from the hopper and immediately put into a glass jar that was sealed with a screw-on plastic lid.
The samples were treated further in order to assess the amount of absorbed water. In altering the amount of water, it was hoped that physiological changes could be seen. This was done by heating in an oven at 150°C for four hours, which is the temperature that the heated screw is maintained at in order to drive off moisture during processing. The samples were weighed before and after treatment in order to calculate the percentage water removed, which is shown below.

<table>
<thead>
<tr>
<th>Sample Time Taken</th>
<th>Sample ID</th>
<th>Jar (g)</th>
<th>Jar + Powder (g)</th>
<th>After treatment (g)</th>
<th>Water Lost (wt%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>04/12/03 4pm</td>
<td>04_04H</td>
<td>204.95</td>
<td>231.69</td>
<td>231.33</td>
<td>1.331</td>
</tr>
<tr>
<td>05/12/03 10am</td>
<td>10_04H</td>
<td>204.95</td>
<td>247.47</td>
<td>247.41</td>
<td>0.141</td>
</tr>
<tr>
<td>05/12/03 10am</td>
<td>10_04W</td>
<td>204.92</td>
<td>240.64</td>
<td>240.59</td>
<td>0.140</td>
</tr>
<tr>
<td>08/12/03 5:30am</td>
<td>05_08H</td>
<td>205.36</td>
<td>226.83</td>
<td>226.74</td>
<td>0.419</td>
</tr>
<tr>
<td>08/12/03 7:45am</td>
<td>07_08H</td>
<td>204.89</td>
<td>226.75</td>
<td>226.66</td>
<td>0.411</td>
</tr>
</tbody>
</table>

Table 4.2.2 Drying Results

The same sample from 05/12/03 at 10am was taken and put in a small Carbolite ELF oven, with a tray of water next to the sample to observe if this increased the amount of moisture in the sample. The test showed that the presence of water at this temperature could not increase the amount of absorbed water in the sample. Therefore, any moisture present in the screw would not be able to affect the amount of absorbed water until the material reaches the hopper and the temperature decreases.

It is difficult given the limited data to find a correlation between moisture content of the sample and ambient weather conditions. The graph below shows inside and outside humidity and temperature with respect to the moisture content of the samples.
Figure 4.2.3 Graph showing approximate correlation between ambient conditions and humidity in sample

The samples taken from the line have shown so far that there may be limited correlation between ambient conditions both inside and outside the factory, although there is inadequate information to confirm this. It is advisable for future work to test the correlation of flow rates from the hopper and moisture content of the sample. If a difference is found, this can be compared with the ambient conditions.

For this reason, a further experiment was conducted in which samples were taken during a day every hour from the line and the humidity in the sample established. The samples were left at 150°C overnight and the amount of water lost measured. This is shown below in the graph, comparing this to ambient conditions.
The humidity inherent in the sample changes throughout the day and has a high value at the beginning of the day before the line begins. The reason for this could be that the sample was taken from the top of the hopper that had been left heating overnight. Since the top of the hopper is vented to enable moisture to escape, there is the possibility that moisture was introduced at a low enough temperature to be absorbed.

Later in the day, the moisture again increases, following a delayed response to outside humidity. This also may be due to the stop-start nature of the process as interruptions take place. This is shown in the following graph that shows the line speed changing throughout the day.
Figure 4.2.5 Graph showing line speed variation throughout the day

It is therefore difficult to establish a clear correlation between line speed, ambient conditions and moisture in sample. For future studies, it would be prudent to compare these line speeds and throughput in the buffer hopper with the seasonal variations.

It is recommended that the correlation between the line speed and other data collected from the line, such as mass in hopper and temperatures, be considered further. This will be studied in detail under different weather conditions and seasons.

It is also suggested that the temperature in the storage bunker be monitored. It would be prudent to conduct an experiment to assess if the temperature of the storage bunker affects if moisture can be absorbed into the limestone.

4.2.2 An Investigation into the Material Properties of the Current Backing Filler Material

It is important to fully investigate the current backing filler material in order to compare to any replacements. If the current material is fully understood, including the manner in which it is transported and flows around the site, then new materials can be considered in the same way. This will aid the implementation of the new material, as the process conditions required will be understood.

The three most important characteristics of an individual particle are its composition, its size and its shape (Coulson, 1999, p.1). These need to be characterised in order to understand the material behaviour.
The samples were each taken and analysed by SEM, which provided both chemical and visual information. The SEM results from the limestone currently in use can be seen below. There is little difference between the samples taken from the hopper or treated in the oven and consequently only a selection is shown here.

Figure 4.2.6 SEM photographs of the sample taken from the hopper at 10am on 4/12/03

Figure 4.2.7 SEM photographs of the sample taken from the hopper at 10am on 4/12/03 and dried

Figure 4.2.8 SEM photographs of the sample taken from the hopper at 4pm on 4/12/03
The SEM results show that the limestone in use currently is mostly composed of CaCO$_3$ and CaMg(CO$_3$)$_2$ with very little impurities. This limestone is shown in the preceding diagrams exhibiting little change in morphology between specimens. The limestone is composed of large angular particles of approximately 10μm and smaller fragments which were of the order 1μm. Limestone is an oxide and therefore may be expected to readily solid-state sinter with such small fragments. However, since the melting point of limestone is so high, temperatures near to $2/3T_m$ are not achieved during the processing route and sintering does not occur.

The particles are irregularly shaped and small, so may lend themselves to mechanical interlocking and surface attraction (Coulson, 1999, p14). It may be that the moisture tends to act as a bonding agent, although this is not obvious from the SEM results. The moisture may give rise to surface tension effects that may lead to the flow problems observed.

Particle size distribution will tend to give information about the flow properties of the material. For example, if the particles are similar sized and regular, flow properties will be better than irregular dissimilar particles. A significant amount of particulate material below 10μm will tend to agglomerate as particles interact and agglomerate in clusters.

In order to assess the current material and offer some insight into its behaviour, a typical sample was taken from the line and sieved. This was done using a brass-framed stainless steel mesh sieve conforming to BS410/1986 and Mettler P1200 scales calibrated to British Standard. The sieving took approximately one hour per sample to ensure that an accurate distribution was obtained.

![Figure 4.2.9 Photograph showing sieves used for analysis](image)
This showed that with the sieving technique used, there were a large amount of fines and no particles above 212μm. The results from each sample were approximately the same with no macro change in particle size seen. A typical result is shown in Table 4.2.3.

<table>
<thead>
<tr>
<th>Sieve Size (μm)</th>
<th>Weight of Sieve S (g)</th>
<th>Weight of Sieve and Powder C (g)</th>
<th>Weight of Powder Distribution P=C-S (g) (%)</th>
<th>Cumulative Distribution (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>500</td>
<td>336.10</td>
<td>336.10</td>
<td>0.00</td>
<td>0.000</td>
</tr>
<tr>
<td>300</td>
<td>316.71</td>
<td>316.71</td>
<td>0.00</td>
<td>0.000</td>
</tr>
<tr>
<td>212</td>
<td>312.70</td>
<td>312.70</td>
<td>0.00</td>
<td>0.000</td>
</tr>
<tr>
<td>150</td>
<td>297.35</td>
<td>297.36</td>
<td>0.01</td>
<td>0.026</td>
</tr>
<tr>
<td>75</td>
<td>293.37</td>
<td>295.52</td>
<td>2.15</td>
<td>5.560</td>
</tr>
<tr>
<td>53</td>
<td>288.87</td>
<td>295.02</td>
<td>6.15</td>
<td>15.904</td>
</tr>
<tr>
<td>Lid</td>
<td>271.55</td>
<td>301.91</td>
<td>30.36</td>
<td>78.510</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td></td>
<td>38.67</td>
<td>100.000</td>
</tr>
</tbody>
</table>

Table 4.2.3 Typical powder distribution of current limestone

This distribution shows a large amount of material less than 53μm. It was shown that if a significant amount of that material is below 10μm then the flow characteristics will be poor. The flow characteristics will be very important industrially as they will help to determine the output rate of product.

The SEM results in conjunction with the sieving results show that a significant amount of material is below the 10μm level and therefore the material may be expected not to flow freely. This was examined in a further experiment designed to demonstrate the flow properties of the material.

Samples were taken and an attempt was made to find the angle of friction of the powder. This is particularly important with regard to the designs of hoppers and bins as a correct angle in the hopper or bin will lead to faster flow through the system and consequently lead to faster through-put of product.

An experiment was set up to observe the flow of the limestone through a slot, and the pressure at the base of a column.
The angle of friction ($\alpha$) is a measure of the frictional forces within the powder and gives an indication of the flow properties under its own weight. The piston placed at the base of a vertical column and filled with small quantities of solid. In this case, the piston will move, but there will come a critical length of solid, $l_c$, whereby if a force is applied, no matter how large, the solid will not be able to be pushed up the tube. The angle between this length and the diameter is the angle of friction.

In the flow through a slot, the material is allowed to flow through a slot in the centre of the base of a two-dimensional bed. The angle between the cleavage separating stationary and flowing material at the horizontal is the angle of friction.
It was found, however that the powder would not flow through the slot, even at elevated temperature and the piston could not be lengthened enough, which suggests a large value of $\alpha$. This would mean that the powder is difficult to manage and a hopper design would have to be considered carefully. This task was therefore out-sourced.

Shear strength tests were carried out using a vertical shear cell of Ajax design and wall friction tests using an Ajax long stroke translational device were performed on a stainless steel plate with a 2B finish. Bulk density was established using a standard measuring cylinder in an ‘as poured’ condition. In each case the sample was heated to 120°C to simulate process conditions.

The results from the Ajax results confirmed that the powder is difficult to handle, as shown by the high Hausner ratio (loose density/maximum density achieved through tapping).

<table>
<thead>
<tr>
<th>As Poured (kg/m3)</th>
<th>Tapped x 10 (kg/m3)</th>
<th>Tapped x 70 (kg/m3)</th>
<th>Hausner Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>976</td>
<td>1081</td>
<td>1359</td>
<td>1.39</td>
</tr>
</tbody>
</table>

*Table 4.2.4 Bulk density variation and Hausner ratio*

The friction angle was determined to be 25.1°, which resulted in a recommended minimum of 73.1° for a conical hopper and 63.1° for Vee hopper design as recommended by the British Materials Handling Board.

Mass flow experiments have shown that the material is difficult to handle and can become compact very easily. It is therefore recommended that the material be placed in constant flow to minimise consolidation. This could be achieved by improving the current aeration system in the hopper to dissuade ‘rat-holing’. It is also suggested that the system is emptied overnight to reduce the chances of the powder compacting with time.

Since the hopper angle used on-line is less than that required, another method of stimulating the material should be considered to increase flow. This may involve the use of refurbished aerators at low pressures to encourage a constant stream of material.

It is also suggested that the hopper is fully emptied on each cycle to decrease the build-up of stationary material on the side. If this material is left, it becomes more compact on each cycle, and so eventually leaves a tunnel of free space for the new material to flow. This reduces the effective angle of the hopper dramatically.
It is recommended that the material be assessed to discover the strength gathered over time, to simulate conditions in use. This experiment would also offer more information about the effects of processing on the material.

4.3 Analysis of Recycled Materials under Consideration as Replacement Backing Filler

The samples that are under consideration for use as a backing filler need to be thoroughly investigated before use. Both the current flow issues and any additional problems should be identified. These will be compared to those found with the existing material. A thorough analysis of the material and its properties would aid the industrial implementation as there will be a greater likelihood of identifying potential problems.

Samples were taken in the ‘as-received’ state of post-industrial recycled limestone from LaFarge. These were from two sites Ashbury (LF_01) and Sheffield (LF_02). These were analysed using SEM and sieving. A bitumen mix was made from LF_01 using the filler to assess its properties and how those differ from the mix made from virgin materials.

The sieving results are as shown below, which reveal significant differences between the recycled filler and that currently in use (Table 4.2.3).

<table>
<thead>
<tr>
<th>Sieve Size (µm)</th>
<th>Weight of Sieve</th>
<th>Weight of Sieve and Powder</th>
<th>Powder Weight</th>
<th>Distribution (%)</th>
<th>Cumulative Distribution (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>500</td>
<td>336.00</td>
<td>336.06</td>
<td>0.06</td>
<td>0.036</td>
<td>0.036</td>
</tr>
<tr>
<td>300</td>
<td>609.48</td>
<td>609.52</td>
<td>0.04</td>
<td>0.024</td>
<td>0.059</td>
</tr>
<tr>
<td>212</td>
<td>599.37</td>
<td>599.54</td>
<td>0.17</td>
<td>0.101</td>
<td>0.160</td>
</tr>
<tr>
<td>150</td>
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<td>580.46</td>
<td>0.30</td>
<td>0.178</td>
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<td>75</td>
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<td>7.299</td>
<td>7.637</td>
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<tr>
<td>53</td>
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<td>578.10</td>
<td>24.40</td>
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<td></td>
<td>168.520</td>
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<td>100.000</td>
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</table>

*Table 4.3.1 Table showing sieving results from LF_01*
<table>
<thead>
<tr>
<th>Sieve Size (μm)</th>
<th>Weight of Sieve and Powder S (g)</th>
<th>Weight of Powder C (g)</th>
<th>Powder Weight P = C - S (g)</th>
<th>2 Distribution (%)</th>
<th>Cumulative Distribution (%)</th>
</tr>
</thead>
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<td>271.28</td>
<td>436.34</td>
<td>165.06</td>
<td>78.205</td>
<td>100.000</td>
</tr>
<tr>
<td>Total</td>
<td>211.06</td>
<td></td>
<td>100.00</td>
<td>100.000</td>
<td></td>
</tr>
</tbody>
</table>

Table 4.3.2 Table showing sieving results from LF_02

As a more complete investigation of the material, which would give some indication of flow properties in conjunction with the sieve analysis, again it was assessed using SEM. Larger particles were sieved out and analysed separately to give an indication of the mix of materials present. These are shown below with each element described highlighted in white.

*Figure 4.3.1* LF_01

*Figure 4.3.2* LF_01 Oxygen

electron Image of Particles >300μm
Figure 4.3.3 LF_01 Silicon

Figure 4.3.4 LF_01 Calcium

Figure 4.3.5 LF_01 Aluminium

Figure 4.3.6 LF_01 Potassium

Figure 4.3.7 LF_02 Electron Image of Particles>300μm

Figure 4.3.8 LF_02 Oxygen
Although a small amount of large particles were found (less than 1%), when these amounts are scaled up to industrial size, the amount needing to be removed from the limestone will be around 300kg per day. The SEM analysis revealed these particles to have an appearance that suggested cleavage failure rather than an agglomeration or sintering, which may suggest hard matter.

These larger particles in the new material from LF_02 mostly consisted of silicates, with a mixture of metallic oxides. These particles will be hard and brittle and therefore unlikely to be crushed under the current systems processes used. The larger particles showed clear differences in the types of material present. The smaller particles (<53μm) also contain silicates, indicating that quartz could be present. These will be useful as filler in that they will tend not to react with the plasticiser if they remain large enough and their surface energy does not become too great.

The larger particles in the new material from LF_01 again consisted of silicates, with a mixture of metals present. However, there was also an equal degree of calcium and silicon present suggesting that limestone may also be a constituent of this mix. In both cases, the smaller particles followed a similar chemical pattern as the larger particles.
If the new materials are to be used in future as part of the backing filler then larger particles above 250µm will have to be completely removed by either sieving or crushing. The LF_02 sample will lend itself more to sieving to remove the larger particles because of their hard nature. The LF_01 sample could be sieved or ground further- although this would tend to further increase the fines in the material and expend a large amount of energy.

LF_01 was used in a bitumen mix and the viscosity measured (Interface work instruction).

<table>
<thead>
<tr>
<th>Crucible Empty</th>
<th>35.730</th>
<th>Crucible Empty</th>
<th>50.787</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crucible With Bitumen</td>
<td>37.758</td>
<td>Crucible With Bitumen</td>
<td>53.155</td>
</tr>
<tr>
<td>After 4 Hours @ 500°C</td>
<td>37.101</td>
<td>After 4 Hours @ 500°C</td>
<td>52.279</td>
</tr>
<tr>
<td>Ash Content</td>
<td>67.6%</td>
<td>Ash Content</td>
<td>63.0%</td>
</tr>
</tbody>
</table>

*Table 4.3.3 Table showing results from ashing test*

<table>
<thead>
<tr>
<th>Temperature (°C)</th>
<th>Viscosity (67.6% Mix)</th>
<th>Viscosity (63.0% mix)</th>
</tr>
</thead>
<tbody>
<tr>
<td>145°C</td>
<td>207,000</td>
<td>200,000</td>
</tr>
<tr>
<td>150°C</td>
<td>165,000</td>
<td>193,000</td>
</tr>
<tr>
<td>155°C</td>
<td>145,000</td>
<td>174,000</td>
</tr>
<tr>
<td>160°C</td>
<td>115,000</td>
<td>140,000</td>
</tr>
<tr>
<td>165°C</td>
<td>93,000</td>
<td>120,000</td>
</tr>
</tbody>
</table>

*Table 4.3.4 Table showing viscosity measurements*

The ashing test shows what quantity of limestone is in the mix as the bitumen is burnt, leaving limestone ash. The viscosities of both mixes are relatively high as they should be in the range 80000-150000 at 150°C. It is therefore suggested that the temperature of application is raised on line or other modifications are made to the material to reduce this.

The results from the viscosity tests show that LF_01 contains too many fines to be considered currently as the mix will be too thick for the current application system. Preliminary results from sieving to remove the larger particles show that some of these fines may be removed in this process (Kemutec, 2004). Part of the continuing investigation will be to investigate sieving techniques that may be used on an industrial scale and would be implemented on-line.
This investigation is ongoing and as part of this, the new industrial sieving techniques will be investigated thoroughly. Experimental sieving will aid this investigation and preliminary results suggest that this method is promising. Other options to remove the larger particles will also be considered.

The SEM work has been useful in determining the chemical composition of the powder. However, this technique has not appeared to offer any advantage in determining changes in morphology due to atmospheric conditions. It would be prudent to analyse any future material under consideration using this method to learn more about the material.

Further investigation of the material is required before altering the filler in the bitumen mix. It may be possible to trial the filler on the bitumen line as the roller applicators will be more forgiving to larger particles than the PVC line that uses a scrapper system.

This investigation will be continuing for the next six months and a replacement filler will be sourced in this time. Industrial techniques for sieving of the replacement fillers will be assessed and a range of options considered for this. This will result in the technique being implemented on-line and there will be a continuing monitoring of the flow of this material.
5 Further Work

This project so far has focused on replacing existing materials in the current product. There are promising alternatives to the face yarn and a fuller analysis of these is required. As part of this, an investigation will be undertaken to assess the current flooring solutions in the market place with samples to be tested.

A full literature review will be produced by month 12 which will encompass the social and technical aspects of flooring and its impact on the environment.

Focus groups are being drawn up from the public and private sector to discuss innovative flooring solutions. These social research groups will be attended as part of an ongoing investigation to seek out new ideas. This will also involve an investigation into past papers on the correlation between quality of life and indoor conditions, which will form part of the literature review.

The backing filler will be replaced in the next six months and the processing conditions monitored as part of a continuing investigation. The behaviour of the material will be supervised to assess if seasonal conditions affect the flow properties.

The data collected from the line will be analysed within the next four weeks to obtain any useful and relevant data regarding the measured flow through the system. Experiments will also be set up to examine the change in material compaction over time and how this can be related back to processing conditions. These will also include the replacement fillers as this investigation continues. Any further candidates for replacement fillers will be investigated thoroughly using sieve analysis, angle of friction tests and SEM.

The Gantt chart shows the approximate timelines of the next steps of the project with the next six months in detail. There will be more opportunity to become involved in longer-term projects based at Interface, as there are fewer courses to undertake as the course progresses.
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Dianne Carter

12-Month Report

01.04.04 - 01.10.04

“Towards Sustainable Design and Manufacture of Textile Flooring Products”
Abstract

"Interface is a ‘flooring solutions’ company with an impressive vision:

“To be the first company that, by its deeds, shows the entire industrial world what sustainability is in all its dimensions: people, process, product, place and profits - by 2020 - and in doing so we will become restorative through the power of influence.”

The EngD research project will be to develop innovative materials and flooring to migrate the textile flooring products towards the company’s vision of sustainability. This will involve a holistic consideration of the supply chain from sourcing renewable raw materials, improving/re-engineering production processes, refurbishment, recycling, downcycling and disposal.”

The initial 6-Month report focused on the industry at present, current products in the marketplace and manufacturing processes. An understanding of the industry was attained and the driving force for change within Interface examined.

This report focuses on improving production processes in order to substitute material within the process. The report makes recommendations for process improvements to achieve the plant requirement of a line speed of 10 m/min.

This work will ultimately result in an increase in recycled material content in the product from 0% to nearly 70% by weight.

The report also continues the review into natural raw materials and their testing for use in the carpet tile. The manner in which British and international standard testing procedures may be applied to an entirely innovative and new flooring solution are examined.

The continuing work will draw focus away from traditional methods of carpet construction and concentrate on completely new and innovative flooring solutions. As part of this, the relationship between customer and product will be examined further.
1 Introduction

1.1 6-Month Report

The first 6-Monthly report described the preliminary investigation into developing innovative flooring solutions. It described the history of Interface Inc, the world’s largest manufacturer of carpet tiles. It is a world leader in industrial ecology and first set out its vision in 1994:

“To be the first company that, by its deeds, shows the entire industrial world what sustainability is in all its dimensions: people, process, product, place and profits - by 2020 - and in doing so we will become restorative through the power of influence.”

Since this vision was set out and the quest began for a sustainable company, many advances have been made in the reduction in carbon intensity by a third, use of 100% renewable energy in Shelf Mills, reduction of greenhouse gases by 46% in absolute terms, reduction of water usage by 78% per carpet tile, the Evergreen lease and RE:Entry systems (Interface sustainability, 2004). However, the basic product that the company produces remains the same - a carpet tile.

In order to become fully sustainable, Interface requires innovative flooring solutions that are from renewable resources, recycled, fully recyclable, with no waste stream and made with 100% renewable energy. There are currently no products within the marketplace that can make this claim.

The initial part of the project was to examine the industry at present, looking at manufacturing methods, current products and their perceived benefits and disadvantages.

The 6-Month report also introduced the investigation into flow problems associated with the tile backing filler material and alternative materials for tile backing, which is concluded in this report.

Focus groups were also attended, as suggested in the 6-month report, investigating the public perception of the floor, which has lead to further innovation.
1.2 Continued Work

The Engineering Doctorate programme has continued to be followed with modules completed in Hands on Audit, Environmental Risk Assessment and Team Building and Leadership Awareness.

This report further extends the work begun in the 6-Month report with regards to finding an alternative for the backing filler. The report focuses on the impact of processing conditions on material transportation and aims to conclude with recommendations for controls of these processing conditions.

Once these conditions can be enforced to renew confidence in the processing of material, an alternative filler may be sought. Candidate replacement filler will be assessed and recommendations made for its use.

This report continues to investigate replacement materials for the current carpet construction. These materials should be renewable, recyleable, biodegradable, recycled or preferably a combination. A review continues of these replacement candidates.

This 12-Month report focuses on replacement materials for the traditional carpet tile construction and hopes to identify some possible candidates. The face yarn and backing filler are the principal constituents considered in this report.
2. An Investigation Into Flow Problems Associated with Tile Backing Filler Material

2.1 Introduction

As described in the 6-Month report this investigation has arisen as a result of the continuing need to introduce a greater amount of recycled content into the products manufactured by Interface. Despite many advances on issues relating to sustainability, since the 2010 vision was set out, the basic goods produced by Interface Europe have not changed significantly.

The greatest increase in recycled content in the product can be achieved by replacing the greatest ingredient by weight- limestone. If this virgin feedstock can be replaced and when used in conjunction with recycled yarn there will be an increase to nearly 70% recycled content from zero.

In order to change the virgin limestone for a product arising from another waste stream, the process and material must first be understood. It was perceived that flow problems with the limestone were causing delays in production, as material could not be delivered rapidly enough.

In short, the equipment was not performing as required with the current material and therefore an alternative material would not yet be viable.

The purpose of this investigation is to alter process settings and understand material characteristics such that the line achieves a process speed of 10 m/min.

In order to fully understand the problems that may be encountered with the substitution of backing material filler, the processing conditions must first be understood and improved, processing parameters defined and future recommendations made.

The substitute material will then be fully investigated and recommendations made for its use.

2.2 Review of Processing

The patented Graphlex backing system is constructed using a double layer of glass fibre reinforcement with a non-woven polypropylene backing and bitumen mix to seal the system together, see figure 2.1.
Figure 2.1 Illustration of Graphlex backing system (Interface Europe, Backing Systems, 2003)

The backing system is assembled before the broadloom yarn is applied. The fibreglass and polypropylene backing systems are brought together with the bitumen mix applied at the rollers as shown.

Figure 2.2 Illustration of backing material being constructed
Figure 2.3 Photograph of bitumen mix being applied at rollers to fibreglass and polypropylene backing

Another layer of fibreglass is added and bitumen is laid on top in the same manner as before, through an additional set of rollers.

Process controls at this point ensure that the appropriate amount of bitumen mix is applied at the appropriate temperature and viscosity in order to maintain a cohesive backing system whilst avoiding problems, such as ‘strike through’ and ‘tear outs’.

In strike through the bitumen travels through the backing material and is visible on the surface, rendering the material below grade. Tear-outs can also occur at this sensitive point in the process, as larger particles or other issues cause tears in the backing material, which traverse along the length of the system and again render the material below grade.

It is therefore important that the bitumen mix that is applied is consistent in its properties, or that process controls are in place such that the properties can be altered readily, or safeguards put in place to reduce the occurrence of faults.

Once the backing system is completed, the tufted yarn is placed on top (see below), it is cooled and subsequently solidified using refrigeration.
The material is then cut to size in 50 cm x 50 cm squares, resulting in some 'window waste' that is currently discarded—although alternatives are being sought.
Since the fibreglass, polypropylene and face yarn are sourced external to Shelf Mills, the bitumen mix is the part of the process over which there is maximum internal control.

The mix is made up of approximately 66% virgin limestone and 34% pre-modified bitumen.

The bitumen is delivered and then stored in external tanks at elevated temperature. The limestone is also stored externally in tank D before being drawn into the system using a series of air blowers to move material.

Figure 2.6 External limestone storage tank leading to colt limestone storage bunker

The limestone is then stored at ambient conditions in the internal sealed colt limestone storage bunker. Motor 53 then drives it into the heated screw, LH5, which is seen at the right of the following diagram.
Figure 2.7 Compound mixing showing heated screw

This screw heats the limestone using a metal jacket filled with thermal oil. This generally heats the limestone to around 150°C, which will drive off some of the moisture in the system at the vent.
The aeromechanical conveyor draws the limestone upwards at an approximate rate of 2600 kg/hr. This conveyor is insulated in order to try to maintain the elevated limestone temperature. More moisture can then be driven off at the top vent.

The limestone then flows into the heated storage bunker, SB56, where the material may be held for some time. A system of air blowing again is used in an effort to ensure that the material does not stagnate and settle. At this point in the system there is a vibratory probe, LT56, which measures the mass of material in the bunker.

The screw conveyor is driven by motor M57, which moves material into the weighed bunker, WB58.
WB58 is designed to hold 210 kg of material that will be dosed into the mix, with a margin of 40 kg. A load cell accurately measures the amount of material in WB58.

The applicators draw a bitumen mix from the compound tank, CT30, at a rate that will depend on the backing weight, face yarn type and construction, line speed and a number of other variables.

The level of CT30 is measured using a radioactive probe. At low level, a signal is sent for the compound mixer, CM28, to dump another load into the tank. After the load is dumped, the compound mixer then needs to begin mixing another batch. The pre-modified bitumen begins to enter the compound mixer before the dosing screw begins to draw off the 210 kg in the weighted bunker.

The weighted bunker will then refill by drawing off material from SB56 via the screw conveyor and the system is supplied again.

In order to calculate how fast this mix must be, we first need to consider the material composition. A sample was taken from the process without face yarn of 100 cm² of mass 31.49 g. This equates to 3149 g m⁻².
The composition of the backing at this time was two sheets of fibreglass of total mass 69.90 g m\(^{-2}\) and one polypropylene sheet of mass 45.00 g m\(^{-2}\).

Therefore the bitumen mix made up 3034 g m\(^{-2}\). Of this nominally two thirds was limestone, i.e. 2023 g m\(^{-2}\).

Since the material is 2 m wide, in order to achieve a line speed of 10 m/min, corresponding to 20 m\(^2\)/min, limestone must flow at 20 x 2023 = 40.5 kg/min.

If a batch size is 210 kg, then the weighted bunker, WB58, must empty and fill in a time of 210/40.5 = 5.18 min, i.e. 5 minutes and 11 seconds.

If this time can be achieved successfully during typical processing conditions, then it will be known that the mix can deliver a line speed of 10 m/min and it will no longer be a hindrance to performance.

If the progress of the mix from applicators back to delivery point is followed, it can be seen that the parameters of the process that the operators can control are:

At the applicators:

- Weight and tension of fibreglass
- Weight and tension of polypropylene
- Transverse movement
- Line speed
- Carpet tension
- Distance between rollers.

At the compound tank:

- Motor drawing off bitumen mix.

At the compound mixer:

- Temperature of thermal oil surrounding mixing tank
- Duration of mix.

At the bitumen tanks, kept hot from delivery:

- Thermal oil jacket controls temperature
- Number of cycles in system contributes to temperature control

At the storage bunkers:
If these parameters can be controlled successfully, it may be that the material flow required can be achieved. The next step in this investigation is to analyse the various parts of the process and their controls in order to facilitate greater movement of bitumen mix to the applicators.

2.3 Analysis of the Individual Parts of the Process

2.3.1 Bunker Dimensions

It has been identified that the critical movement of limestone material in the system is from the heated storage bunker, SB56, to the weighted bunker, WB58, and consequently dosing from WB58 to the compound mixer, CM28.

It was decided initially to assess whether mass flow could be maintained through the bunkers without assistance from further agitation methods. The results from experiments included in the 6-monthly report showed that the material did not flow readily.

Shear strength tests were carried out using an Ajax vertical shear cell. Wall friction tests using an Ajax long stroke translational device were performed on a stainless steel plate with a 2B finish.

The friction angle was determined to be 25.1°, which resulted in a recommended minimum angle of 73.1° for a conical hopper and 63.1° for Vee hopper design, as recommended by the British Materials Handling Board (Ajax, 2004).
Figure 2.10 Current hopper dimensions

The dimensions of the current hopper design (see above), do not meet these requirements. It was noted that agitation was required in order to move material readily through the system.
However, changing the complete hopper design was deemed inappropriate as the system was designed to achieve the required material movement in order to satisfy requirements for a line speed of 10 m/min.

2.3.2 Investigation of Agitation within Storage Bunker

In the current set-up, the heated storage bunker, SB56, utilises blown, dried air to agitate material inside. This method was proving ineffective with blockages reported frequently and material obviously building up around the edges of the hopper.

![Diagram of Aerator Design](image)

**Figure 2.11 Aerator design**

The manner in which the limestone should be agitated need to be considered carefully as investigations of the powder showed that it is prone to packing readily.

Experiments conducted on the material showed that from a loose packed density of around 900 kg m\(^{-3}\), after sieving through a brass sieve of 500 \(\mu\)m, the density of the limestone could increase to 1400 kg m\(^{-3}\). This can increase by a further 4% over time without further agitation. The average of 5 results is shown in the table below.

<table>
<thead>
<tr>
<th>Average initial untapped volume (kg m(^{-3}))</th>
<th>Tapped x 60 (kg m(^{-3}))</th>
<th>Tapped x 90 (kg m(^{-3}))</th>
<th>Overnight (kg m(^{-3}))</th>
<th>4 Days (kg m(^{-3}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>898</td>
<td>1142</td>
<td>1386</td>
<td>1394</td>
<td>1441</td>
</tr>
</tbody>
</table>

*Table 2.1 Results from tapping experiments showing increase in powder bulk density*

It follows from this that in the aerator a method of agitation that utilises least vibration is desirable.
Upon investigation of the aerators within the hopper, it was discovered that during a clear-up process, designed to remove the compacted material at the edges of SB56 by mechanical means, the pads providing the air blown system had become damaged.

The pads were aerators designed to blow air into the limestone at low pressure in order to facilitate its flow. Immediate action followed to replace the aerators that resulted in an immediate improvement in flow.

The external controls available on the aerators enabled the time of aeration and maximum pressure to be altered. At a line speed of 8.1 m/min (variable), these parameters were altered for a minimum of 45 minutes in order to observe any variation in the flow rate of material from the weighed bunker.

The results showed that over the range of parameters investigated, a pressure of 0.6 bar and time on: off of 4.5 seconds: 1.5 seconds offered the least time of fill and empty of WB58.

<table>
<thead>
<tr>
<th>Pressure (bar)</th>
<th>Average Empty (min:sec)</th>
<th>Average Fill (min:sec)</th>
<th>Total (min:sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.9</td>
<td>02:29</td>
<td>04:18</td>
<td>06:47</td>
</tr>
<tr>
<td>0.8</td>
<td>02:29</td>
<td>04:34</td>
<td>07:03</td>
</tr>
<tr>
<td>0.7</td>
<td>02:26</td>
<td>03:47</td>
<td>06:13</td>
</tr>
<tr>
<td>0.6</td>
<td>02:29</td>
<td>03:14</td>
<td>05:44</td>
</tr>
</tbody>
</table>

Table 2.2 Effect of variation in air pressure of aerators on average empty and fill times of WB58 (time on: time off set at 4.5:1.5)

<table>
<thead>
<tr>
<th>Time On: Off (sec)</th>
<th>Time On (%)</th>
<th>Average Empty (min:sec)</th>
<th>Average Fill (min:sec)</th>
<th>Total (min:sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4:0</td>
<td>100</td>
<td>02:25</td>
<td>03:20</td>
<td>05:45</td>
</tr>
<tr>
<td>10:1</td>
<td>91</td>
<td>02:30</td>
<td>03:59</td>
<td>06:29</td>
</tr>
<tr>
<td>4.5:1.5</td>
<td>75</td>
<td>02:30</td>
<td>03:14</td>
<td>05:44</td>
</tr>
<tr>
<td>4:4</td>
<td>50</td>
<td>02:27</td>
<td>03:25</td>
<td>05:52</td>
</tr>
<tr>
<td>1.5:9</td>
<td>14</td>
<td>02:28</td>
<td>03:40</td>
<td>06:08</td>
</tr>
<tr>
<td>0:4</td>
<td>0</td>
<td>02:27</td>
<td>04:38</td>
<td>07:05</td>
</tr>
</tbody>
</table>

Table 2.3 Effect of variation in time on: time off of aerators on average empty and fill times of WB58 (air pressure set at 0.6 bar)
WT58 was chosen as the probe, as it has been shown that the required fill and empty time of this bunker for the desired line speed of 10 m/min is 5 minutes 11 seconds. WT58 is also a load cell, more accurate than the vibratory probe LT56.

With the changes made to the aerators, it was shown that the time could be reduced to 5 minutes 44 seconds- a great reduction on the original timings of over 7 minutes without aeration.

It is therefore shown that changing the method of agitation in SB56 increases the flowability of the material and consequently its movement into WB58 and reduces the time needed for each mix.

2.3.3 Batch Size/Mass in Bunker

In order to increase the amount of bitumen mix reaching the applicators in any given time, more material must flow from the compound tank. A bigger batch size within the same time would satisfy this need. However, the compound mixer takes 110 seconds per mix. It has been shown that material cannot fill the weighted bunker, WB58, within this time limit. Since this rate will not be increased by a bigger batch size, the only consequence will be a greater time to fill and empty WB58. Therefore a bigger batch would not increase the amount of material arriving at the applicators.

The mass transferred from WB58 to the compound mixer is therefore 210 kg per mix. Throughout previous experiments it has been shown that the transfer of material from WB58 to the compound mixer takes approximately 2 minutes 30 seconds. The design of the dosing screw indicates that a rate of 3.1 kg/s can be achieved, when ordinarily only 1.4 kg/s is achieved.

The settings of the bunker are such that it begins to fill at 200 kg and reaches high level at 232 kg. Therefore there is little scope for variation in the emptying of this bunker, as it needs to be filled as soon as possible. Observing the measurements from the weighted probe, WT58, it can be seen that the bunker always reduces to a very low level and therefore changing the fill levels will have little effect.
However, in the course of usual operations, the perception is that in order to increase the amount of material flow through the system, SB56 should remain as full as possible. Results from the probe LT56 show that SB56 continuously contains material. This is shown in figure 2.12.

WT58 shows the filling and emptying of the weighed bunker. As it begins to empty material moves into the compound mixer through the dosing screw. Once the weighed bunker has dumped the appropriate amount of material, it can begin filling again.

As the screw conveyor begins to move material from SB56 to WB58 it can be seen that LT56 begins to drop as WT58 increases. The aeromechanical conveyor draws material into SB56 as the low fill level of SB56 is reached. At the maximum fill level of WB58, WT58 is again at its maximum, whilst LT56 is at minimum. The aeromechanical conveyor continues to draw material into SB56 and so LT56 continues to rise to its maximum fill level. It is at this point that the aeromechanical conveyor will cease and the fill level remains constant until more material is required.

Figure 2.12 Graph showing typical values for WT58, LT56 and line speed (DB20_DW46)
The peaks on LT56 and WT58 show when valves are opened to the screw conveyor and the dosing screw as a back-pressure causes a false mass reading on the probes.

At a line speed of 7.5m/min the begin fill and stop fill levels of SB56 were changed in order to try to decrease the fill time of WB58. The settings were kept for a minimum of 30 minutes and results shown below.

<table>
<thead>
<tr>
<th>Range (kg)</th>
<th>Empty Time</th>
<th>Fill Time</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>210-220</td>
<td>0:02:27</td>
<td>0:03:51</td>
<td>0:06:18</td>
</tr>
<tr>
<td>125-150</td>
<td>0:02:24</td>
<td>0:03:36</td>
<td>0:06:01</td>
</tr>
<tr>
<td>125-140</td>
<td>0:02:28</td>
<td>0:03:28</td>
<td>0:05:56</td>
</tr>
<tr>
<td>130-145</td>
<td>0:02:26</td>
<td>0:03:17</td>
<td>0:05:43</td>
</tr>
</tbody>
</table>

*Table 2.4 Showing variation in fill time of WB58 with variation in material in SB56*

Table 2.4 shows that reducing the amount of material remaining static in WB56 can reduce the fill time of WB58 by 35 seconds.
Figure 2.13 Graph showing fill and empty levels of SB56 and effect on WT58

Figure 2.13 shows that LT 56 is fully empty for approximately 1 minute and 30 seconds consistently. During this time, material is flowing directly from the slower aeromechanical conveyor to the screw conveyor. Therefore the system is not performing at its optimum.

Taking the above sample for this day, it can be seen that if the correct adjustments can be made to WB56 so that it empties to a minimum every time (a reduction of 1 minute 30 seconds of direct transfer from the slower aeromechanical conveyor at 0.72 kg/s to the screw conveyor at 1.2 kg/s), then the fill time of WB58 can be further reduced.

If the differences in the rates of the conveyors are taken into account, the material over this time that is transported from the aeromechanical conveyor is 64.8 kg, whereas if it were direct from the screw conveyor the time taken for this amount to be transported would be 54 seconds. Therefore a further 36 seconds could be saved if the material during this time were direct from SB56 to WB58 and not from further back in the system.

Therefore, if the system is set up to enable WB56 to fully empty and then refill and the same time as WB58 is emptying, the cycle time can be reduced from the observed time of 5 minutes 43 seconds to 5 minutes and 7 seconds. This is within the time limit of 5 minutes 11 seconds required.

2.3.4 Hold Time

It has been shown that the shorter the period of time for which the material remains static, the more efficiently it will flow through the system and into the compound mixer.

The amount of time for which the material is stagnant will depend on three factors, i.e. the maximum fill level, the minimum fill level and line speed. If the line speed is low, then the fill levels of SB56 need to remain low, in order that WB58 fills slowly and the material remains stagnant for the minimum time.
2.3.5 Performance of Modified System

During the course of this investigation, the inverters attached to the motors M54, M57 and M59 were increased in order to try to increase the material movement throughout the system. Data recorded at 10 m/min showed that the motors had increased the delivery rates of the aeromechanical conveyor and screws by a small margin, even though SB56 did not empty fully again.

<table>
<thead>
<tr>
<th>Aeromechanical conveyor (kg/s)</th>
<th>Screw conveyor (kg/s)</th>
<th>Dosing screw (kg/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Before</td>
<td>0.80</td>
<td>1.05</td>
</tr>
<tr>
<td>After</td>
<td>0.85</td>
<td>1.08</td>
</tr>
</tbody>
</table>

*Table 2.5 Showing increased rates caused by motors*

*Figure 2.14 Graph showing line running at 10m/min*
With the range of modifications in place, the data above has been taken from a 10m/min line trial. It clearly shows a consistent fill time of WB58 of 3 minutes 14 seconds and empty time of average 1 minute 15 seconds. This total cycle time of 4 minutes 29 seconds is well below that required by the line speed of 10m/min.

2.4 Introduction of Alternative Limestone Supply

2.4.1 Background and Scope

It was thought originally that changes in material properties, evident during delivery differences, were responsible for the perceived ‘bottle-neck’. However, it has been shown in the previous section that any material differences can be compensated for within the processing parameters.

A further part of this investigation was to assess the changes in material properties throughout normal processing and complete a comparison with candidate replacement materials.

This investigation compares some promising candidates that arise from the waste stream of an external source. Recent trials with these candidates show that processing parameters can be altered to compensate for these material changes.

The virgin feedstock material was examined in the 6-monthly report and compared to an alternative LF_01. Further information can be found in the next section.

In addition, LF_01 was sieved using an external process and this was compared to the standard as-received LF_01.

The candidate materials were introduced to the system at the limestone heater, LH5 and continued in the normal process cycle to the applicators in the bitumen mix where they were applied as part of the backing system.

The three most important characteristics of an individual particle indicating its capacity for flow are its shape, size and composition (Coulson, 1999). These are considered in the next section.
2.4.2 Material Characteristics

a) Chemical Composition

SEM analysis from previous work indicates that the virgin feedstock is mostly pure material. There would therefore be greater problems with the introduction of alternative filler and different chemical interactions could occur. The pure material does not suffer many adverse chemical reactions, as it is a relatively stable material.

Experiments using the candidate alternative as filler will show if problems are encountered in making a homogeneous bitumen mix (see section 2.4.4).

b) Particle Shape

SEM analysis was conducted (Carter, 2004) showing the particles from replacement candidates and virgin feedstock are irregularly shaped (see below). This tends to lead to poor flowability (Coulson, 1999).

Figure 2.15 SEM analysis showing typical original virgin material
Figure 2.16 SEM analysis showing larger particles from replacement candidate

However, analysis of particle shape could only ascertain that the replacement candidate appeared to come from cleavage-type fractures. Both were assessed to be poor shapes for flow.

c) Particle Size

Extensive investigations were carried out regarding particle size. Samples of the candidate material were taken before and after processing through the aeromechanical conveyor and compared to the virgin feedstock standard. This was conducted using the sieving method described in the 6-monthly report.

<table>
<thead>
<tr>
<th>Type</th>
<th>Particle size distribution (%) microns</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>&gt; 300</td>
</tr>
<tr>
<td>Un-sieved - As received</td>
<td>2.20</td>
</tr>
<tr>
<td>Un-sieved - After screw</td>
<td>0.37</td>
</tr>
<tr>
<td>Sieved - As received</td>
<td>0.08</td>
</tr>
<tr>
<td>Sieved - After Screw</td>
<td>0.00</td>
</tr>
<tr>
<td>Standard aggregate</td>
<td>0.05</td>
</tr>
</tbody>
</table>

Table 2.6 Sieve analysis of candidate replacement filler (LF_01)

The analysis shows that there are larger particles present in the candidate filler when un-sieved. It is thought that these particles may cause tear-outs when they arrive at the applicators. However evidence from the trial indicates that no problems were encountered, except for a number of short draglines.
2.4.3 Moisture Content

Moisture is introduced into the sample below 70°C. This moisture will not cause visual changes to the material (SEM analysis shows this), but will probably interact with the limestone causing it to become more 'sticky' and difficult to flow. The current processing conditions can drive off moisture effectively to below 0.3%, but this can vary throughout the day.

Comparing the moisture in the materials after the aeromechanical conveyor shows that the candidate materials contain considerably more moisture at any given time (See below).

<table>
<thead>
<tr>
<th>Type</th>
<th>Normal</th>
<th>Sieved</th>
<th>Un-sieved</th>
</tr>
</thead>
<tbody>
<tr>
<td>Moisture (%)</td>
<td>0.075</td>
<td>0.25</td>
<td>0.11</td>
</tr>
</tbody>
</table>

Table 2.7 Moisture variation during trial

However, monitoring of the virgin material at this vent in SB56 has shown that moisture can vary considerably with processing, compensating for these changes. Therefore, it is believed the processing changes can compensate for any changes in material properties encountered.

2.5 Bitumen Mix

The increase in smaller particles, in the LF_01 material, may cause an increase in viscosity of the bitumen mix as they will have a greater surface area per unit mass. Therefore samples were taken from the applicators during the trial and compared to standard.

Samples were taken from the compound tank, CT30, and compared to the standard mix. Mixes 2 to 4 were the sieved filler, 5 to 7 were the un-sieved filler and 1 and 8 were mixed with the standard filler.

<table>
<thead>
<tr>
<th></th>
<th>Std Filler</th>
<th>Secondary Aggregate Filler</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Mix</td>
<td>% Filler</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>150°C</td>
<td>69.52</td>
<td>69.65</td>
<td>103,000</td>
</tr>
<tr>
<td>155°C</td>
<td>69.69</td>
<td>96,000</td>
<td>121,000</td>
</tr>
<tr>
<td>165°C</td>
<td>60,800</td>
<td>65,000</td>
<td>85,000</td>
</tr>
</tbody>
</table>

Table 2.8 Viscosity changes of bitumen mix during trial measured at temperature (mPa.s)
This data shows clearly that the candidate for replacement filler possesses viscosity at the upper end and beyond of the standard specification of 80,000-150,000 mPa.s at 150°C.

However, processing controls are in place via the heating system, which may alter the temperature of application of the bitumen and enable it to be a viable alternative.

2.6 Summary

Initially it was theorised that changes in material properties would compromise the ability of the process to achieve the desired throughput of 10m/min. This investigation has shown that processing conditions can be varied such that they can facilitate the material flow and achieve the desired throughput consistently.

This result means that the virgin feedstock can be substituted in the process with confidence in the machinery, process and method.

As a consequence the substituted material could be from a recycled source, and when used in conjunction with Interface’s recycled face yarn this results in an immediate increase to over 70% recycled product content.

It is recommended that the candidate replacements be taken to full large-scale trials.
3. Alternative Materials

3.1 Background

In order to achieve the vision of Interface set out in 1994, the basic materials that make up their products must be made from alternative sources. Currently nylon, polypropylene, bitumen, virgin limestone, polyvinyl chloride (PVC), and other inclusions are unsustainable and cannot form part of the future in which this vision is fulfilled.

In order to make the materials sustainable, they must be a combination of recycled, recyclable, made from renewable feedstock or biodegradable. There are flooring solutions in the market place that begin to satisfy these requirements, for example hemp yarn (Earthweave, 2004) and wooden laminates (Purewoodfloors, 2004).

This chapter focuses on the method of construction and tests of the flooring that results in some candidates being dismissed as replacements. A number of prototypes have been constructed and tested in recent times that have not attained the required standards for contract carpet under historical testing.

If an entirely new system of flooring were to be introduced, testing methods would also have to be introduced in order to assess the performance of the product in use. It is important to consider the way in which a new test method may be introduced for a new flooring system.

It is important that any system developed continues to satisfy the needs the customer has for a flooring solution and the associated expectations.

3.2 History of Testing

Carpets are tested using a variety of methods that are intended to mimic their use in practice. These tests are designed to ensure that the customer receives a product that satisfies their needs; they are blind to the substances that make up the carpet. It may be that new tests are required to assess a flooring solution that does not follow the traditional method of construction, but offers different values.

Carpets, no matter what their base material, undergo a series of tests in order to assess their contract level- the number given to a carpet to define its capability in use. Natural materials are difficult to test under these criteria as by their nature they vary between batches and consistent properties are often not achieved.
The British Textile Technology Group (BTTG) is historically the independent testing house that is responsible for validating test procedures. It was this house that developed the current carpet testing based on woollen carpets.

BTTG was formed in 1988 following the merger of the Shirley Institute and the Wool Industries Research Organisation (WIRA), which had been involved in testing materials since 1919. It has a number of subsidiaries including BTTG Ltd (established 2003), Fire Technical Service (FTS), British Carpet Technical Centre (BCTC) and Advanced Materials Services Ltd (Nunney, 2004).

It is an entirely independent organisation, funded by a variety of methods including commercial testing. BTTG prides itself on its stringent objectivity and even offers an expert witness service. BTTG also participates in EU funded work, contributing to the development of European standards and acting as the official UK testing body for European ecolabelling and product certification schemes.

The tests offered at BTTG are varied and not restricted to carpets and textiles. All floor coverings can be tested at the centres, using similar methods to those used in the carpet industry.

WIRA developed the current carpet testing procedures based on woollen carpets. These tests focus on abrasion resistance, dynamic loading, static loading, flammability and appearance retention.

Dynamic loading tests have been described in the 6-Month report as the Vetterman drum and Hexapod tests. The Lisson Tretrad test (BS EN 1963:1998) also describes a method of abrasion resistance measurement (see figure below).

![Figure 3.1 Lisson Tretrad test close showing abrasion as feet slip on specimen](image)
Static loading is tested using BS 4939:1987, ISO 3416-1986, where the thickness reduction in carpet pile is measured after application of mass for 24 hours and during recovery.

Flammability is measured using the hot metal nut method that follows BS 4790:1987. Other European standards have been introduced for flammability as carpet is officially classified as a construction material (Nunney, 2004).

Even the squareness, size and straightness of carpet tiles are measured using a British standard- BS 5921:1980.

Appearance retention assessment follows a set of guidelines set out in BS EN 1471:1997. The appearance is assessed after test using an expert eyewitness. These experts are assessed regularly on their work and usually an average of three eyewitnesses are taken into account. They score the change in appearance on a scale of 0-4 within a tolerance of 0.8. The appearance assessment is conducted in a standardised light box with samples resting upon a rotating table.

It is believed that in 2008 the Construction Products Directive (Council Directive 89/106/CE) will become compulsory for all construction materials (Nunney, 2004), of which carpet is a class. It defines essential characteristics for health and safety and CE marking which are discussed with the relevant trade associations (Deputy Prime Minister, 2004).

Legislation is on the way that will require measurements of volatile organic compounds (VOCs) and some legislation will be on the table that assesses sustainability and recyclability.

In order to introduce a new testing method to qualify with new legislation that is internationally accepted, a number of steps must be taken and committees involved.

Standardised equipment must be searched for- in particular for other floor coverings. Prototypes are then built which can test a range of products.

Repeatability and reproducibility is key at this stage in the process. An accuracy and precision statement is made at this time, which must relate the test to what occurs in practice.

If the standard is accepted as a British Standard, BSEN, it may be that a standard of another country may offer similar tests. If this is the case, an ISO committee assesses the standard and again constructs a review. The new ISO standard will then supersede the British Standard and the latter is withdrawn.
Therefore if an entirely new material and flooring solution were suggested, the method of testing would have to be considered. It will therefore take a considerable time period before both the testing method and material are assessed and accepted.

It follows that the raw materials suggested previously should be investigated further before being dismissed, as they can be tested using conventional methods.

### 3.3 Raw Material Performance

Wool was the traditional material used in carpet manufacturing and wool is a product made from renewable resources (see figure 3.2).

![Figure 3.2 Renewable resources at play](image)

In the 1960s viscose became more fashionable and was tried as a cheaper alternative. However, its wear properties were poor, it flattened and burnt easily in comparison to wool (Colton, 2004).

Nylon was then added at 20% by volume. This increased the durability considerably, whilst retaining a similar feel (CRI, Primer, 2003). For example, wool carpet typically survives 7-9,000 revolutions of an abrasion machine (BS EN 1813:1998), whereas a 20% nylon addition increases the survival to 30-50,000 revolutions.
The parallel expansions in the plastics, petrochemical and oil industries resulted in a vast reduction in cost and a consequential boom in the plastics industry (Subramanian, 2000). Hence the use of nylon began to increase considerably at the expense of natural materials.

In 2003 the use of wool had declined to its lowest point in the carpet industry, as shown in figure 3.3.

![Pie chart](image)

**Figure 3.3. Annual fibre consumption in US by weight (The Carpet Primer, 2003)**

Initially the appearance retention of nylon was poor, as it appeared to soil easily. There followed a series of developments to change the cross-section to that of a bulk continuous filament that had an uneven cross-section (see below).

![Cross-sectional shapes](image)

**Figure 3.4 Changes in cross-sectional shape of fibre from circle to triangle to lobal triangular or square with four holes**

This resulted in an enhanced ability of the polymer to hide reflective light and soil. A finish was also applied to combat soil.
It seems that in order for a new material to begin to compete in this market, one of three things must occur:

1. Carpet is accepted as a fashion item and a shorter lifetime becomes acceptable.
2. Petrochemicals become so expensive they are no longer viable.
3. A natural raw material or one from renewable feedstock arises that is capable of similar performance to nylon.

Option 1 will be considered in the 18-Month report and the consequences for the environment discussed. It may be that a product with a lower environmental impact per product, with shorter lifetime is better for the environment overall than a product with high environmental impact with a long lifetime.

Option 2 is an issue that is currently being discussed at great length in the media and environmental journals that is not discussed here. International and political pressures are constantly affecting oil prices. There is also political pressure upon companies to use fewer petrochemicals in production that could drive prices up.

Option 3 is an option that is viable for investigation in the first stages of this project, given the position of Interface.

It has been stated that the inherent nature of raw materials is such that there will be changes in properties depending on seasonal variations, conditioning, breed/type etc. Even if these factors can be standardised there are other considerations to be taken into account during processing.

If a natural, variable fibre is fed into a production line, one method of trying to minimise variability is to utilise blending systems. This is not a new problem, as it has existed for centuries and been overcome in some ways.

One model upon which to base the processing of alternative material is that which is used in the woollen spinning industry.

The woollen spinners invoke a great deal of mixing and aerating processes in the processing of wool fibre into yarn. Its aim for around 10 different processes is to achieve uniformity of fibre through carding and building up of yarn.

Depending on the requirements of the final yarn, the wool blends that form the ingredients differ. For example, for carpets British wool is ideal as it is coarser—although black hairs are detrimental to appearance, the Mediterranean and Middle East provide softer wool due to their climates and New Zealand tends to produce a whiter wool with no black hairs.
It may be that blending different natural raw material fibres in this same manner may provide a mixed property yarn that retains appearance after testing.

Hemp fibre is one that is widely considered as a material for the future (Hemcore, 1998, Hempworld, 2004, Marijuananews, 2004). It is the highest fibre yield of any crop- in hot weather the crop can grow to 4m high in only 12 weeks. With no agrochemicals used in its production, fibres three or four times stronger and vastly reduced quantities of water required in comparison to cotton, the advantages are clear.

Trials of hemp fibre have been conducted at Interface Europe, Shelf Mills that have shown that there is a need for good quality hemp to satisfy demand for consistent wear properties (Colton, 2004).

The hemp fibre used has a cross-section that is a polygon with rounded peaks (Weiner, 2003). It begins to show signs of scale, detrimental to appearance after use. Figure 3.5 shows a cross-section of a hemp stem with the two fibre types indicated.

![Hemp stem cross-section](image)

*Figure 3.5 Hemp stem cross-section (Henfaes, 2004)*
Cotton, jute and Icelandic wool have also been trialed as alternatives that appear to exhibit reduced performance at increased cost. None of these alternatives provide the same performance in the same manner as nylon or olefin.

It is therefore reasonable to conclude that at present there is no natural raw material that is as consistent, durable, cheap and versatile as nylon in carpet construction.

It is suggested that in future work fibres may be assessed more closely and processing introduced that may improve properties, for example, fibre coating, mixing, alternative sources and blends.

4. Further Work

The next 6 months will focus on alternative solutions to the sustainable flooring problem, which do not involve traditional carpet construction, but rather focuses on innovative solutions that may be totally novel and diverse. New product development at Interface is diversifying and consequently the scope for new concepts is expanding.

A literature review will be conducted before 22nd November 2004 concerning biopolymers and their properties. Included in this literature review will be an examination of the current flooring industry and recent innovative products.

The benefits that a floor offers to a consumer will also be examined in the next report, in terms of well-being as well as practicality. As part of this investigation, the implications to the consumer of making carpet a fashion item will be considered.

Making flooring more fashionable and short-term has environmental implications that need to be considered on a case-by-case basis. The general environmental concerns will however be considered as part of this investigation.

The Gantt chart for the next three years is shown in figure 4.1, but will be added to in greater detail as the projects take shape in the next few months.
Figure 4.1 Gantt chart showing four-year progress.
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Dianne Carter

18-Month Report

01.10.04 - 01.04.05

“Towards Sustainable Design and Manufacture of Textile Flooring Products”
Abstract

The two previous progress reports at months 6 and 12 have focused on reviewing and improvement of current technologies within Interface Europe. Production processes were improved in order to achieve consistent, reliable feed at an increased line speed of 10m/min.

Material and flow characteristics of the carpet tile backing filler were assessed throughout the manufacturing process. This allowed the material to be substituted with one from a recycled source, which in turn increased the total recycled content of the product to 70% by weight. This saves over 5,000 tonnes of material per annum from landfill and introduces a system that may be implemented across the business.

The overall project aims are to develop innovative materials and flooring including a holistic consideration of the supply chain. This report, for the period October 2004 to April 2005, has moved the focus from existing to new technologies. The new technologies include a consideration of the development of biopolymer films and coatings. This report concludes with a revised outline project plan for the remainder of the EngD with the period up to October 2005 shown in greater detail.

To become sustainable products cannot rely on non-renewable sources, including energy. This report examines the potential for chemical feedstocks derived from renewable (including biological) resources.

Traditional methods of manufacture of textile flooring that were described in the 6-month report are energy intensive and use a great deal of processes. Other flooring in the market place, such as vinyl, often utilises a number of harmful chemicals. These studies in the previous reports have shown that an innovative solution is required.

In order to design an entirely new flooring product, a background review of other flooring has been conducted in this report. An assessment of current flooring products, their applications, fitting, properties and disposal is presented.

These reviews of the characteristics that a floor must have in order to satisfy the consumer have given rise to the Pour-A-Flor concept. Biopolymers are reviewed here as a pre-cursor to the Pour-A-Flor product, which is derived from renewable technologies. The concept is currently under investigation and will form the basis of the next 6 months work.
1 Introduction

1.1 Summary of Work Described in 12-Month Report

The 12-month report focused on the textile flooring industry at present, in particular current products in the market place and manufacturing processes. This showed that the industry utilised a large number of processes in order to achieve a consistent product.

The processes used at Interface Europe, Shelf Mills were examined carefully in order to optimise production. An investigation into the flow problems associated with the tile backing filler material concluded with a number of recommendations. There were enhancements made to the backing system that have been consistently used. These enhancements have resulted in a line speed increase of 25%. This improved line speed has resulted in renewed confidence in the system.

An investigation was also undertaken into possible alternatives for the tile backing filler material and recommendations were made for this material to be used in the backing system. This work has resulted in an investment of £40,000 into a system of sieving that will allow this recycled material to be introduced into the tile backing. This work potentially results in an increase in recycled content of the product from 0 to 70%, by mass.

This investigation has been described in the paper “Introducing Recycled Feedstock: Material Flow Problems in the Manufacture of Carpet Tile Backing”, presented at the 2005 Conference for the Engineering Doctorate in Environmental Technology on 11th January.

Clearly the energy-intensive nature of these processes and the use of non-renewable materials show that sustainability cannot be achieved with this traditional product. Thus, a more innovative solution is required.

The examination of some natural raw material feedstock showed that the traditional method of flooring construction cannot provide the same performance with these substitutions. Hence, an alternative method of construction is required.

1.2 Project Direction in the Current Reporting Period

The next stage of this Engineering Doctorate focuses on the “innovative materials and flooring products” that will “migrate the textile flooring products towards the company’s vision of sustainability”, that was described in the initial project description.
In order to develop innovative solutions for flooring, the benefits that flooring offers must first be considered. Any innovative flooring product must offer at least the same qualities and attributes received by the customer from traditional flooring without adverse effect. This consideration results in a need to evaluate a background review of flooring and performance criteria, shown in section 3.2.

The application methods of current floorings are varied and numerous. These are examined in this report in chapter 3 as a pre-cursor to the introduction of a proposed new technology.

Pour-A-Flor is a concept that has arisen as a result of innovations exercises and the examination of state-of-the-art technologies. This concept is a first step towards Interface’s vision of sustainability and is described fully in chapter 4.

This concept forms the basis of the next stage of this EngD research project and will provide a number of research opportunities. The project plan for Pour-A-Flor is shown in chapter 5 as it forms the majority of the work for the next 6 months.
2 Renewable Feedstock

2.1 Background

The supply chain of the carpet tile has been examined which has shown that the greatest environmental impacts arise from the embodied energy in nylon. Although it contributes only 8% of the embodied mass, it contains 38% of the total embodied energy and contributes 49% to the global warming potential (GWP) (Interface LCA, 2002).

There is a great deal of processing that occurs during the manufacture of a carpet tile as each of the components is manufactured separately before assembly (Carter, 2004). Life cycle analyses show that this processing is an important factor in the environmental burden of the carpet tile, although it is dwarfed by the environmental impacts of the petrochemical-based materials.

In trying to reduce the environmental impact of flooring, renewable feedstock is a natural first consideration in substituting for the non-renewable feedstock. The 6 and 12-month reports have discussed natural raw materials. Traditional flooring products made from natural raw materials generally do not pass the same performance criteria that their petrochemical cousins do (Nunney, 2004).

Natural fibres such as wool and hemp are not generally used in the heavy contract category, as they cannot pass the stricter performance criteria. Natural fibres generally have lower tensile strengths, elongation to failure and durability than nylon fibres that are typically used in textile flooring (DTI, 2003). Nylon fibres can be manufactured in longer lengths than are found in natural fibres and therefore can be manipulated more readily in the manufacturing processes of textile flooring (Carter, 2004).

Other renewable feedstocks that remain to be considered are those that involve a number of processing steps such as starch-based polymers and oil-based resins. This processing, described in section 2.3.2, is less desirable than using raw materials in their natural, or near-natural, state as this generally uses more energy during processing and increases the length of supply chain from producer to consumer. The longer the supply chain, the greater the difficulty in identifying the larger environmental impacts and the less chance of achieving the control over the cycle needed to reduce these impacts.
Since the 1990s polymers based on renewable feedstocks and natural fibres have been used in a number of applications, such as biodegradable capsules for drug delivery systems (PURAC, 2004), non-woven material in the replacement of human tissue (Eagles et al, 1997), waste bags and packaging material (Van de Velde, 2002).

The main driver for the increased use of these materials has been environmental superiority in terms of a reduced overall environmental impact along with their biodegradability. These factors may be expected to continue to drive their development, as they cannot currently compete in many other features, such as cost and performance, as volume and consequently research investment is still small. Biopolymers made up less than 2% of the plastics market in the EU in 2001 (ERRME, 2001).

Biodegradable polymers can also be made from petrochemical feedstock. However, in the context of this research project only biopolymers that are made from more than 50 wt% renewable resources will be considered.

Life cycle analyses have been carried out that show that polymers based on renewable feedstock are better overall than their petrochemical based counterparts (Patel et al, 2003). As an example, Starch polymer pellets require 24-75% lower energy than polyethylene and GWP is 20-80% lower throughout a number of life cycle analyses with different disposal routes considered.

However, there are many more factors to consider in making the choice to go from non-renewable to renewable resources such as transport, genetic modification (GM) issues and localised social impacts. The transport issues can be great as unprocessed bio-mass is generally bulky and the end product small volume in comparison to the small size of petrochemicals with a ready network of transportation. GM has been an issue at the forefront of European matters (IsiS, 2005, BBC, 2000 and UK Environment 2005) and is viewed with suspicion by the general public. Social impacts can be great in localised environments as potential food crops are substituted for those crops that can be sold further afield at a premium (CIGB, 2005).

This chapter does not answer all these concerns, but rather intends to give a brief review of the biopolymer industry in its current state; describing the processing, properties and applications of some of the commercial biopolymers available. This chapter also considers some of the options for the development of biopolymers in the future that will also be expanded upon as part of the examination of innovative flooring solutions in chapter 4.
Biopolymers are generally made from renewable feedstock that is processed and treated in order to become the finished product. Although the source of the material is generally a big improvement on the petrochemical feedstock, the processing involved utilises a number of chemical steps. The current range of renewable feedstocks that can be processed into biopolymers are first examined.

2.2 Renewable Feedstocks

2.2.1 Background

In pre- and early-industrialised societies, many end products are derived from renewable feedstocks. In developed economies, since the 1940's petrochemical-based fossil fuels have been increasingly used, replacing renewable feedstocks that were used extensively before the sudden increase in the petrochemical industry. Petrochemicals offer cheaper, more durable and versatile materials for applications such as fabrics, pharmaceuticals, packaging and indeed flooring.

Renewable feedstocks have recently been revisited in the pharmaceutical and chemical industry as the search begins for alternative chemicals to fulfil different roles (Roberts, 2004). The number of new chemicals that can be derived from non-renewable sources is becoming exhausted as this area has been focused on for many years (Parker, 2004). This has been research and industry driven as the threat of future legislation as well as the vast possibilities from nature drive long-term developments.

Renewable raw materials, including oils, starch, sugar and cellulose are converted via physical, chemical or biochemical processes into chemical intermediates such as polymers, lubricants, solvents and surfactants, known as platform chemicals (Hardy, 2004). These platform chemicals are then transformed via further processing into usable chemicals before they are mixed and packaged for distribution.

The key in substituting renewable materials is that they offer alternative and/or improved properties such as biodegradability and/or improved functionality as well as reduced environmental impacts.

It is rarely possible to substitute a renewable for petrochemical based ingredients unless the replacement is chemically 'identical' (Parker, 2004), as different trace impurities or different levels of the same impurity can have profound effects. However, it is the very nature of crops grown in different climates, growing medium and/or conditions that give rise to their variable qualities.
Currently, technology has not developed to cope fully with these variations in the same way that numerous carbon-based molecules are extracted and blended in the petrochemical industry. Although rapid analysis and predictive modelling can begin to overcome these variations, as has been shown by innovative biopolymer researchers (A and F, 2005).

Biopolymer research is a central issue for Agrotechnology and Food Innovations. They develop and model processes and research the relationship between structure and function. B!PP also offer a tailor-made research facility and development team for the consumer needs as consultants.

It should be noted that GM is offering solutions to some of the variability issues by metabolic engineering to increase plant productivity and increasing the range of tissues producing the metabolite. Also transgenic plants could produce foreign proteins, although the technology is currently controversial. GM can avoid variability in supply and quality-matching production to demand. This results in a reduced land requirement and has been employed commercially to produce ginseng in Canada (Punja, 2003).

However, GM is still viewed with suspicion, especially in Europe, by the general public. There are social as well as environmental issues associated with its introduction and it is still rare to receive a license in the UK for a large-scale development in this vein.

There are already some cautionary tales, to be noted such as that of Biopol (poly(3-hydroxybutyrate)). This was initially produced by ICI and expected to become a multi-thousand tonne biodegradable plastics business (Hardy, 2004). This did not happen due to price and performance comparisons with conventional materials such as polypropylene. There needs to be a niche market for the product, such as medical or packaging applications before it can become successful in the current marketplace against traditional competitors (Parker, 2004).

There are a multitude of factors that may affect the platform chemical produced by a biomass refinery, based on the concept of the traditional oil refinery, shown in figure 1.
Figure 1. The Biorefinery Concept (Hardy, 2004)

This figure shows the bulk biomass material as the feedstock, which is then processed mechanically and extractives removed. These extractives can be easily separated in the form of waxes, phenolics, oils etc that can be used as ingredients in more complicated mixtures without further modifications.

The bulk material that remains after this initial processing is then further processed using thermal, chemical or microbial means in order to extract further useful simple chemicals. These chemical intermediates, the platform chemicals, are then transformed with processing to more specific chemicals for use in high value products.

The bulk biomass material dictates the chemicals that can be extracted from the product. However, the environmental credentials of the biomass are enhanced significantly if the materials are otherwise wasted, for example, potato starch in the chip-making process (Murphy, 2005). This biomass is available in a multitude of sources such as the 4 million tonnes of wheat straw and 14 million tonnes of waste paper produced in the UK annually (Hardy, 2004).

The integrated extraction of the platform chemicals can be performed in a number of ways and these are further considered in the next section.
2.2.2 Conversion from Raw Materials

This section describes the possible ways of converting raw materials into useful chemicals. This research area is still developing and therefore the potential for the future of this industry is also examined.

There are four possible methods of converting biomass into chemicals and useful products.

- Thermal
- Chemical
- Microbial
- Mechanical

Thermal methods of extracting chemicals from the biomass could include

i) Combustion into hot gases and consequently heat and electricity
ii) Gasification and then conversion to heat, methane, methanol and gasoline
iii) Pyrolysis into gases, char and hydrocarbons for use as fuel
iv) Liquidation or hydrothermal conversion into hydrocarbons that can be used as fuel, oil and other derivatives.

The difficulty with utilising raw materials in these ways is that the feedstock may be bulky and difficult to handle, without the technical experience associated with petrochemicals. This is often the case with natural materials, as they are not inherently designed for use; they are designed to grow and reproduce. Its very nature as an organic material dictates that it may contain moisture detrimental to processing (Hardy, 2004).
Renewable Oil International is developing a mobile pyrolysis facility that can deal with 5 dry tons of renewable material per day. This goes some way to addressing the needs of the biopolymer industry in the UK, although major developments are being made outside the UK, as shown by A and F and B!PP. The figure above shows that the facility is still small scale and a full-scale plant is the next step for development.

A major source of environmental impact shown in life cycle analyses frequently arises from transport of material. It is preferable to ensure the source of material is close to where it will be used and disposed of. It is therefore prudent to consider the role of the UK in the biopolymer industry.

The UK is not a leading biopolymer producer. It has lagged behind Europe and concentrates on the production of products that dissolve in the body for the medical industry. The future of the UK in the biopolymer industry, either as a producer, manufacturer or researcher was considered as part of this literature review and is discussed in the next section.
2.2.3 Future Road Mapping

The UK textile industry has been focused mainly in rural areas in the UK. This leads to the possibility that the raw materials can be produced close to the site of processing and use. This reduces overall environmental impact as there are limited transport concerns and can increase social sustainability by stimulating rural development.

This section describes the potential for the UK to be more involved in the biopolymer industry as a producer, researcher, processor or user. This is important, as it will provide closer links to the textile industry and potential for further study.

There were several cases identified for the UK to become part of the expanding biopolymer industry (Hardy, 2004):

- The UK becomes specialist in new crops to produce renewable chemicals
- Chemicals are produced from crops that the UK presently or potentially could grow well
- Platform chemicals are bought in from outside the UK and transformed using existing chemical processes
- UK technology is developed and licensed externally to produce end use chemicals.

Each of these scenarios requires extensive co-operation between industries. There is a need for co-ordinated national and regional policies in order to implement any of these developments, as long as market demand is high.

The UK is known for its wheat, barley and rape (National Statistics, 2005). These crops can all be used to produce secondary chemicals such as ethanol, levulinic acid, succinic acid, lactic acid and 1,3-propandiol (Hardy, 2004). These in turn can be formed into products with added value such as perfumes, biopolymers and pharmaceuticals.

The UK that has only 18.5 Mha devoted to agriculture, as its economy is based on service provision. Practically the UK cannot provide a reliable feedstock at an acceptable price to convert to a biopolymer without compromising its agricultural needs and contending with a varying climate. It is impractical for the UK to import feedstock with consistent properties, such as fibre length, chemistry and growth rate, as the transport costs involved may be too great- both economically and environmentally.
If the UK were to consider research and development as a specialisation in biopolymers there are many opportunities available for expanding technology. There are a number of advances that have been made internationally that result in the commercial use of biopolymers and these will be discussed in the next section.

2.3 Commercial Biopolymers

2.3.1 Background

Commercial biopolymers can be found in a variety of applications such as polylactic acid (PLA) used as face yarn in carpet tiles (Interface, 2003), EverCorn Resin™ used in drinks containers (Japan Cornstarch, 2005) and another starch based polymer used in dog toys (Novamont, 2005).

There are some natural polymers to be found such as proteins, nucleic acids, polysaccharides, lignin and rubber (MacGregor, 1980). These are rarely used in their natural state, and are modified to purify and alter their chemical constituents in order to offer more versatility and efficacy.

More recently biopolymers have arisen due to a number of extraction processes and chemical pathways becoming available such as the cross-linking of epoxidised natural oils (Boquillon, 2000). Starch-based polymers have been extensively investigated (Patel, 2003, Johnson, 2002, Van de Velde, 2002) and their properties are well documented. However, their mechanical performance does not generally reach the level of their petrochemical counterparts and therefore they cannot be used at the same level in applications.

PLA, for example, has been used as an alternative to nylon in the carpet industry, although it does not provide the long-term aesthetic properties of its nylon cousin and flattens readily (Colton, 2004). Consequently nylon will continue to be used until PLA can be modified such that it performs as well in heavy contract situations.

There is a range of data given in the literature for biopolymer performance and these are shown in table 1.
<table>
<thead>
<tr>
<th>Properties</th>
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<th>Type of Biopolymer</th>
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<th>Poly-e-caprolactone</th>
<th>Polyhydroxybutyrate</th>
<th>Typical Polyester</th>
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<td>233</td>
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Table 1: Physical properties of various biopolymers (Van de Velde, 2002)

All the polymers shown above are polyesters, which when manufactured via the petrochemical route provide one of the toughest of plastic films with excellent fatigue and shear strength, making them useful for a number of applications. They also provide good resistance to humidity, acids, greases, oils and solvents (Callister, 2000).

The Young’s Modulus and tensile strength can be improved by using natural fibres as part of a composite system and the rule of mixtures to calculate the most effective volume fraction. This can all be achieved during the processing of the biopolymers, which would lend the biopolymers to a greater range of applications, such as car panels.

If the properties of these biopolymers can be increased then there is a greater chance of using them in more applications more readily. There are a multitude of biopolymers that are available and these may be modified in many ways. The key to their modification is their processing. The next section describes the way in which select biopolymers are processed.

2.3.2 Processing

As previously mentioned there are a number of ways to extract platform chemicals from renewable resources. The most common chemicals extracted for use in the biopolymer industry are starch and cellulose, as they can be derived from a variety of sources easily (Plank, 2005).
Starch-based biopolymers are extracted from biomass in a number of commercial systems. Cargill Dow for example extracts PLA from cornstarch (Cargill Dow, 2005), and this process is described below.

Corn is milled, separating starch from the raw material. Unrefined dextrose is then processed from the starch, which is in turn fermented into lactic acid. This is condensed into a dimer, purified and polymerised using a solvent-free melt process. This can result in a number of polymers with differing molecular weights that can be used in a variety of applications.

Other commercial methods of transforming corn into a biopolymer rely on utilising the entire grain (Vegemat, 2005). The starch and proteins break down in the presence of a plastifier in a thermo-mechanical environment to form a thermoplastic. The fibres are used as fillers and the lipids as lubricants. This results in a material that is processed into pellets that can be used in a conventional injection-moulding machine.

Biomer use bacteria feeding off sugars in an aqueous medium to produce polyhydroxybutyric acid (PHB) (Biomer, 2005). The bacteria are washed and the PHB extracted using a solvent that is then recovered as the PHB precipitates in a solution with water. PHB is currently being used for shampoo containers (Azom, 2005), as the material offers a good balance of high stiffness and toughness.

The applications of these polymers are limited by both their cost and restriction in processing. However, PLA has found large-scale commercial use in the textile industry, although its performance then becomes the restricting factor. There are a number of applications that have been developed.

2.3.3 Applications

Biopolymers have found their niche in a number of applications where their properties can be advantageous. The most common advantage of these biopolymers is often their degradability, which allows the materials loop to be completed. However, this needs to be strictly controlled and British Standard EN 13432:2000 describes the biodegradability conditions.

Biopolymers are used in adhesives, fibres, animal products, personal care, medical, garden and more commonly packaging applications (Biopolymer.net, 2005).
Figure 3. PLA products produced by Cargill Dow (Cargill Dow, 2005)

The processing of these biopolymers can restrict their applications to those that are thermoformed, as a number cannot be formed into films without purification steps during extraction. However, starch blends have been used in biodegradable packaging trials in Germany (Klauss, 2003).

This examination of the applications of biopolymers has shown that in considering their use in a flooring product, the method of processing must be thoroughly investigated in order that something practicable is developed. Biopolymers are not as easily processed as their petrochemical counterparts and therefore their application may be restricted.

However, the primary concern when considering biopolymers as part of a flooring system is the material properties. The material must be fit for the purpose of which it is designed. The specifications of a floor are considered in chapter 3, which show that although the biopolymers cannot entirely replace petrochemicals in a traditional flooring product, they may be useful in other constructions.
2.3.4 Disposal

After considering the applications of biopolymers the next step in the life cycle to analyse is the disposal. There are significant moves with mainly European legislation towards producer responsibility at the end of the useful life of a product.

Interface is already addressing this issue with the Evergreen Lease system that offers the take-back of carpet tiles at the end of their life. However, biopolymers may offer solutions to complete the lifecycle more simply, as currently product is recycled for use as backing or re-used. One of the most important considerations when deciding to use a biopolymer is its biodegradability in composting conditions.

It has been shown that consumers will readily accept biodegradable packaging as a substitute for conventional packaging systems (Klauss, 2003). Given the correct facilities for sorting, this trial showed that packing recovery rates could be achieved of the order of 80%. However, specialist facilities for biodegrading are often required with these biopolymers as they can produce unstable products such as methane and may require a trigger for degrading.

There are a number of chemical mechanisms that take place in order to degrade a polymer. Natural macromolecules are generally degraded in biological systems by hydrolysis followed by oxidation (Chandra, 1998). Fungi and bacteria can be used in conjunction with enzymes that lower the activation energy required of the degradation process and therefore increase reaction rates in an environment that would otherwise not be favourable. However, these enzymes, bacteria or fungi must be introduced in a controlled environment such as a composting bin.

This has implications for the life cycle of the biopolymer as there may be increased environmental costs either in transportation or the manufacture of specialist mobile facilities. Therefore there may be reduced environmental impacts in recycling or incinerating a biopolymer rather than biodegrading.

The life cycle of the biopolymer shows that there are a number of potential applications, but the difficulty is that they need to compete commercially with the petrochemical industry that has had a head start of around 70 years and often advantageous mechanical properties. Biopolymers need to find niche applications that may justify their current increased cost, before economies of scale can be introduced.
This analysis has shown that there are possibilities for the use of biopolymers, but they do need careful consideration and extensive examination. With respect to the flooring industry, a biopolymer must either offer unique properties, application or, at least, similar mechanical properties to a polymer in use. This project will begin to assess how biopolymers and renewable feedstocks can be used in the flooring industry in innovative and interesting ways.

The use of biopolymers as innovative flooring is discussed further in chapter 4 when Pour-A-Flor is examined. This is a novel flooring system using biopolymer resin as a base for a number of design ideas. This shows promise as a flooring system and can be tested using traditional means.
3 Flooring

3.1 Introduction

This focus of this project is now moving towards more innovative flooring solutions. In order to provide the context for these new and exciting products, the benefits of a floor will be considered. This includes consideration of the way that different floors affect comfort level. There are different ways that different consumers interact with a floor and these will be examined.

Flooring has evolved over several thousand years as consumer tastes and requirements have changed. In early homes the floor was just a patch of dry ground. This is still true in many parts of the world, such as Africa, where the weather is warm and temperate. Dry ground is a good, inexpensive surface that can easily be levelled and modified to create a floor. Hay, straw and cow dung are sometimes also added to the surface and trampled down to create a surface almost as hard as cement.

Figure 1. Typical interior of African hut (Patty in Africa, 2005)

Figure 1 shows that with a dry ground floor, an attempt has been made to add colour and texture. This shows that despite the simple functionality of this floor, something more is required.
During the Middle Ages in Europe floors were often made of trampled down debris as people sometimes shared their living space with their animals—although generally in different rooms. Although the floor was made from waste, a primitive attempt was made to improve the interior by adding mint to the refuse. Crushing the mint underfoot would create deodorising smells, akin to a modern day air freshener.

In early North American homes sand was often placed on the floor, sometimes in decorative patterns and swept out of the room when the litter and debris became excessive. Peanut and sunflower seed shells were added to the floor so that they could be crushed underfoot, producing oil, which retained and settled the dirt (Huntington, 2005).

Other early forms of decorating the floor led to the Indian tradition of rangoli, which is a painting made from rice flour and petals created for a special occasion or to greet visitors. This idea of a welcome mat has been developed further in recent years more as a functional entity than a decorative piece.

Stone floors have been used since the Egyptian times as coloured tiles were used to create mosaic. This can be traced from 5,000 years ago, through to the Roman Empire. The Romans then discovered another more sophisticated benefit of using stone floors—underfloor heating. A fire would provide heat through the space underneath the tile floor. Tiles came in and out of fashion over the next couple of thousand years and underfloor heating has remained a preserve of the more well off (Huntington, 2005).

Wooden planks were first used as floors in the Middle Ages, before being sanded, sealed with varnish and decorated in later years. Stains were used to imprint decorative patterns on the floor. This is a simple, natural floor, which is made from a material widely available as a construction material.

The oldest known rug discovered was from around 400 BC (the Pazyryk carpet), although there is evidence that carpet-weaving dates back to around 4,000 years ago in Egypt, Mesopotamia and the Middle East. The carpet industry has continued to grow and diversify through the industrial revolution and the movement to tufted carpets from woven, which is described in the 6 and 12-month reports (Carter, 2004).

Other types of resilient flooring such as rubber, cork, asphalt, vinyl and linoleum have been in use since the late 1800s and these are now second only to carpet in terms of sales.
These technologies have developed over several thousands of years in order to adapt to the materials locally available as well as practical needs. Decoration has influenced heavily the method of construction of these floors. For example, the Romans used small tiles in their mosaic construction in order to create more intricate patterns.

![Figure 2. Decorative Roman Pavement (Canterbury Roman Museum, 2004)](image)

The history of flooring has shown that not every development made in flooring has an associated practical benefit. This leads to the conclusion that there is more value from a floor than simply function- there are social attributes that are important too. These will be summarised in the next section.

### 3.2 Flooring Requirements

It is difficult to access the requirements placed on a floor without a great deal of social research, since there are not only practical but also emotional needs associated with the purchase of a floor. This section examines the way in which different consumers relate to their flooring and the reasons behind the choices they currently make. The way in which consumers are open to other alternatives are also examined.

Consumers make strong distinctions between categories of floor (O’Neill, 2003). They see wood and ceramic as permanent flooring and vinyl, laminate and carpet as temporary floor coverings. They also see the buying process as either practical, e.g. laminate and vinyl, or emotional, e.g. hardwood and ceramic.
Interface Europe, in conjunction with Ibbotson Research and Planning, conducted research into the requirements of flooring from a customer point of view (I R and P, 2004). The aim of the research was to understand, explore and test theories with respect to how different consumers regarded their flooring needs.

Five extended creative focus groups of consumers were segmented according to lifestyle. Ten interviews with experts were also conducted with interior designers, retailers and style editors. The aim of these interviews was to assess the trends in the flooring marketplace. They did not consider the needs of the consumer, focusing on general trends and therefore are not relevant to this section. However, they may be taken into account when considering the placing of a new product in the marketplace, which will follow in future reports.

The consumer groups were homeowners who made their own decisions on their home décor. They were a mix of gender, ages, economic group, living in a range of properties (age and type). The focus groups were divided into the five consumer group life stages: young singles/professionals, partners/no children (DINKies), young families, older families and empty nesters.

The focus of the groups was to establish the current flooring throughout their homes, related motivations for purchase and satisfaction levels. There was a need to establish what emotional and functional factors have to be fulfilled by each flooring material to meet the needs of different rooms. Creative stimulus was provided to establish what inspires the consumers and what characteristics make up the perfect flooring.

The creative stimulus was provided in the forms of items and images and the consumers were asked to pick ones that inspired them in some way with the brief of creating the perfect flooring for a given room. The items ranged from bubble wrap to soft cloth material to stones to mirrors.

The results of the investigation show that each group of homeowners have different emotional attachments to their flooring. For example, the empty nesters tend to prefer traditional products to suit their older properties such as quality carpets, ceramic tiles and vinyl tiles. They seek familiarity, value for money and functionality.

Older families again tend to have older, larger homes with natural materials a heavy feature of their flooring- wood and stone tiles in particular. Carpets are very popular with this group.
Young families are generally situated in traditional semi-detached or terraced housing. They have a variety of flooring from traditional carpets throughout the home to laminate, ceramic tiles and some carpet tiles.

DINKies have a range of home types, with carpet remaining very popular. Wooden floorboards are also popular, along with stone or quarry tiles.

Singles live in smaller homes such as flats or terraces with original features like floorboards or carpets. They are the group most open to a variety of flooring such as coir, stone, wood, laminate, tiles and lino.

This initial survey showed that there were distinct differences between the ways in which each group furnished their home. Each group had a different relationship with their flooring. As the groups got older they expected more luxurious flooring that was more durable. The younger groups tended to prefer to experiment more with their flooring choices and were more likely to go for the less expensive options. Therefore age is as much a factor as lifestyle in determining preferences.

The reasons behind the decisions made with choosing flooring were also examined. These showed that the empty nesters had high disposable incomes, but they are careful spenders- they want value for money. They also require flooring with little or no DIY and little maintenance. Their priorities are comfort and texture.

Families are divided by their income more than the age of their children. The lower income families prefer mass-market products, whereas those with more income desire luxury, design and texture. Ease of clean and functionality are still important to both.

DINKies prefer designer and innovative products, they are therefore more likely to lead trends, or follow quickly. They have limited constraints on their choice of flooring and are more likely to spend more.

Singles are style conscious, but aware of the age of their house and the way in which natural materials such as wood can be used within this environment. They generally have a lower income and therefore constraints do exist. They are not typical users of carpet.

The creative stimulus also showed how open these groups were to new ideas when asked to give ideas for their perfect room. Firstly they were asked to describe the function of the room. These are summarised below:

Kitchens
• Durable, waterproof, sealed and easy to clean
• There is less of a need/desire for texture-
• There are concerns about dirt trapping and hygiene
• There is a likelihood of barefoot walking
• There should be a consideration of users- children, pets etc
• “Industrial floors” are emerging as a popular choice
• Laminates and vinyl remain popular

Dining Rooms

• The requirements depend on design and function- a separate room for evening/formal occasions is very different to an open family room used 3 times a day for 7 days a week
• A more formal room tends to have the same demands as lounges
• A more functional room tends to have the same demands as kitchens

Lounges

• Texture and comfort is vital for most in the lounge
• This is the showpiece room and therefore high quality is required
• Carpets are more popular in this room but wood in combination with luxurious rugs are also popular

Conservatories

• The needs of a conservatory depend on the purpose
• To relax, to play or to dine
• It is considered an extension of the family room, dining room or lounge
• Flooring will typically reflect what is used in these connecting rooms- a continuation of a theme

Utility rooms

• These are similar to kitchens- they are more demands for impermeable material which makes some consumers nervous about modular flooring

Bathrooms: There are two schools of thinking for bathrooms that are very distinct

• Impermeability, which tends to be more in child and male dominated households. This results in a more quirky and design-conscious choice
• Texture, which tends to dominate in adult only households or en-suite bathrooms. Consumers are looking for a more luxurious feel
Bedrooms

- The master bedroom is emotionally a cocoon and therefore soft, warm textures are preferred. It is in this room that the consumer retains the most emotional attachment to the floor. Lino and modular flooring is far less common in this area with wood and laminates sometimes featuring.
- The children’s bedrooms tend to be carpeted, with innovative, quirky designs more common. As this area frequently doubles as a play area consumers are more open to modular flooring here.
- Guest bedrooms follow similar lines to the master bedroom- but on a lower budget.

The Home Office

- This is more a functional room
- There is less texture but it does tend to mimic the surrounding rooms, hall or landing

Play Rooms

- It is rare in the UK that there is the luxury of space to have a play room
- If there is a separate area it is often open to all sorts of possibilities with different textures, designs and colours
- It needs to be safe, bright and stimulating

Halls and Landings

- These are high traffic areas and therefore the flooring needs to be durable, hard-wearing and easy to clean
- This area is viewed as the ‘face’ of the house and therefore needs to be in line with current design trends
- Carpet is still very popular in this area, in line with the need for texture and softness, particularly upstairs where it connects with bedrooms and bathrooms

This research shows that there are distinctly different requirements for different areas of the house. The needs of flooring cannot be generalised. There is more emotional attachment to flooring in particular areas, whereas in others practicality takes precedence.
The creative stimulus was used to draw out phrases about the perfect rooms for each segment. For example, the perfect kitchen was described by the empty nesters as soft underfoot, hardwearing, practical naturals and colour was considered here. In contrast the young families chose words such as practical, safe and subtle. The young professionals chose a mix of materials and suggested phrases like bold, fun and contemporary.

This research showed that there were a mix of requirements for a floor depending on life stage and situation. Different segments and areas resulted in a need for a range of properties from luxurious to practical to safe to funky, fun and contemporary.

It seems that although people do not often consider the floor an important part of their lives, it does provide some social value and they consider that it can add value to their homes. If we consider the industrial market, however, we find that there are fewer emotional attachments to the floor.

3.3 Industrial Flooring Systems

3.3.1 Categories of Flooring

There are many industrial flooring systems in the marketplace. The focus of this type of flooring is generally in practicality rather than any emotional attachments. Therefore there are entirely different kinds of flooring that emerge in this sector.

There are a number of applications for industrial flooring, which are wide-ranging. These are described by category in the British Standards. It is important that these are described, as industrial flooring has distinct requirements based on the different types of flooring rather than the situation in which it is placed.

British Standards describe the tests that each flooring type must undergo in order to be certified under different categories. Resilient floor coverings describe linoleum, polyvinyl chloride, rubber, cork and corklinoleum.

BS EN 13329 describes the specification requirements and test methods of laminate floor coverings. A laminate is described as “a floor covering with a surface layer consisting of a surface layer of one or more thin sheets of a fibrous material (usually paper) impregnated with aminplastic thermosetting resins (usually melamine)... bonded or directly pressed on a substrate.... finished with a backing”.

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BS EN 548 describes the specification requirements for plain and decorative linoleum. Linoleum cement is defined as “a binder in linoleum consisting of a mixture of linseed oil and/or other vegetable dry oils, rosin and drying oil catalysts, which is converted to a semi-elastic mass by an oxidative curing process”. Linoleum is also defined in the same standard as “a product produced by calendaring one or more layers of a homogeneous mixture of linoleum cement, cork and/or wood floor, pigments and inorganic fillers containing a fibrous reinforcement and/or fibrous backing”.

When considering the products in the marketplace that are available for use on the floor there are a number of screeds, mortars and plasters. The methods for testing these are found in BS EN 4551, which covers a different type of testing to that already defined. These tests concentrate on stiffening rate and strength of cubes, not testing the product in conditions similar to that in use. However a similar test that is used again is the ‘resistance to penetration’, similar to the static loading tests used for flooring.

The range of British Standards under the classification number 6319 describe an assortment of tests that are suitable for testing resin and polymer/cement compositions for use in construction.

A cold-curing resin system is a “resin system that can harden without the external application of heat”. Filler is defined as “a solid material in powder, granular or fibrous form that is added to a synthetic resin system to… modify flow properties before cure”. Hardener is “a material that chemically combines with a synthetic resin to give a hardened product”.

Resin concrete is described as a “blend of resin and hardener with graded aggregate where a significant proportion of the aggregate is retained on a 5.0mm BS 410 test sieve”. However the standard goes on to describe resin mortar as “a blend of resin and hardener with graded aggregate where a small proportion of the aggregate is retained on a 5.0mm BS 410 test sieve.

A thermosetting resin is “a resin that, when hardened, is converted into an essentially infusible and insoluble product”. BS EN 669 describes tests that can be used to measure the dimensional stability of the covering that may be useful for comparison to future technologies.

These descriptions are useful in that they tell us where a future technology may lie. However, each of these categories describes tests on the particular flooring that is ‘fit-for-purpose’. Therefore, as described in the 12-month report (Carter, October 2004), a new technology will potentially require new testing methods to show its capability.
In order to consider if a system is suitable, it must be appropriate for the purpose that it is intended. The application method used for industrial flooring often limits its use. The restrictions on this sector will be examined.

### 3.3.2 Applications

Industrial flooring covers such different environments as offices, warehouses and exhibitions. Therefore a wide range of flooring is found in this market. This section will describe the application of typical industrial flooring and shows that specialist skills are required in this sector.

The case study chosen is one for the fitting of vinyl as it is typical industrial flooring that is applied on a regular basis. This involves several application steps.

Firstly the previous flooring is removed using a vibrating blade or other method and the subfloor is exposed (figure 3). The debris is removed at this time.

![Figure 3. Old floor being removed](image)

Once the old floor is removed, a sticky subfloor remains. This is covered with a screed that is applied by hand, using a levelled trowel. This is then left to set for some time- preferably overnight.

Once the screed has dried, a damp-proof membrane may be applied. This is shown as the black mark in figure 4.
Once the screed is ready, the vinyl is cut to size and laid in place. It is measured carefully, although there are many seams, and roughly cut the edges that will be trimmed later.

An adhesive is applied using a grooved trowel that ensures that the correct amount is applied. A sweeping motion is used to spread the adhesive and ensure that all areas are covered (figure 5). It is then left to “go off” for a time according to the manufacturers instructions.

The vinyl is then placed over the adhesive and brushed to even out the texture. The edges are softened with heat (figure 6) and carefully cut to the exact size required. The seams are welded together to finish off the vinyl and create a complete product.
Figure 6. The edges of the vinyl are softened with heat before being cut to size

This description shows that there is a great deal of attention and skill required in order to fit what could be thought of as a simple vinyl floor. The range of applications and types of industrial flooring are as diverse as the skills needed to fit them.

The methods of applications include painting (floor paints, epoxy glosses), brushing (primers, etchers), rollers (concrete repair, epoxy resins), troweling (concretes, adhesives, mortars), shovelling (bitu-mend) to laying the finished product (carpets, underlay, vinyl). This is by no means a comprehensive list.

Each application depends on the type of flooring used. There is of course a great deal of flooring types available for industry. Some of the categories are described in order to give some idea of the range of materials and properties available.

3.4 Summary

This chapter has shown that in the home environment there is a great deal of emotional attachment to flooring- although often unconsciously. There are differing demands placed on the floor that have evolved through different cultures having different environments. The requirements of an industrial floor are diverse, which has resulted in a multitude of options for the floor.

We can conclude that an innovative flooring solution is more likely to be accepted by certain social groups and experts than others. Therefore the innovative flooring solution must be carefully researched and marketed in a particular way.

There are a large variety of flooring options available in the market place- although they are not simple to fit. There may be a niche in the market for a floor that is easy to fit, simple, yet versatile enough to include a number of flexible design systems. This concept will be taken further in the next section.
4 Pour-A-Flor

4.1 Background

The way in which Interface Europe generates new flooring solutions through the Process Materials Research (PMR) department has been described in the 6-Month report (Carter, 2004). The PMR Manager has the ultimate responsibility for agreeing projects, setting objectives and a project leader.

However, a new role of Innovations Director was recently created, directly reporting to the Senior Vice President, Central Marketing. This role has responsibility for an Innovations Pipeline of ideas and products and bringing these wider projects to completion.

As part of this new brief, on the 12th and 13th May 2004 Interface Europe facilitated an Innovation Workshop with a number of experts. The aim of this workshop was to formulate new ideas for the floor coverings and interiors market based on the principles of sustainable living and restorative behaviour.

The experts were from a wide range of experience and backgrounds designed to give a good mixture of ideas and creative inputs. There were textile technicians, marketers, consultants, sustainable designers, academics, sustainable thinkers, mathematicians and engineers.

The first day began with an introduction to Interface and the ideas of Ray Anderson, who has created the company’s 2020 vision. There then began a debate regarding the challenges laid out with a view to build preliminary concepts on the future state of working and living spaces.

A number of issues that face Interface were identified as part of this first session that require consideration as part of the future of this project. In particular a number of new concepts and ideas for Interface to develop were suggested. There were a number of ideas that evolved as part of this which were direct flooring suggestions. One of these was described as Por Man’s Floor- a pourable biopolymer flooring that is entirely biodegradable.

This concept was developed until it became know as Pour-A-Flor (PAF) and is defined by the fuller concept brief below.
4.2 Concept Brief

4.2.1 Concept Description

The following section describes the ideal performance characteristics of the Pour-A-Flor system. The PAF concept is a modular flooring system. The concept is positioned at the top of the waste hierarchy in that it generates no waste at installation, is made from renewable resources and is entirely biodegradable. The material taken from the Earth when PAF is made is returned in a usable form.

PAF is a multipart system and the concept offers flexibility with creativity as the floor is literally poured either onto an existing surface or a new design. PAF is a design-upwards system, in that it encourages the customer to begin creating a room from the base upwards and consider the floor as a major design tool.

The underlay, or design substrate, that makes up the design has a range of possibilities. This provides the visual mood for the surface as it provides design flexibility in colours, shapes, patterns and brand identity. Interface would suggest design ideas and sell templates for use within PAF to encourage individual customer creativity.

The PAF is self-levelling and offers a hygienic seal for the floor, which will be designed to be an impervious barrier to water and microorganisms so making PAF ideal for wet areas. The top surface for PAF will be provided in a one or two-part system that can be purchased off-the-shelf in liquid form. The floor will be designed to set-to-touch quickly (2 hours maximum) and to harden for contract use within a designated time (6 hours maximum).

The floor is easy to clean, as the surface can be rough (through the addition of particles into PAF), but not fibrous. The surface can be vacuumed and mopped using conventional methods without damage to the surface.

PAF can be removed from the substrate and the biodegrading initiated through the application of a ‘remover’. This could be composted in-situ or in a designated composting facility without the need for further treatment by over 90% in 90 days as defined by the ISO standards (Murphy, 2004).

Collaborations and partnerships are essential to the success of this concept. Interface requires external partners to provide technical assistance to provide initial biopolymer material. Technical assistance will be required from academic partnerships to assess the structure and surface chemistry of the prototypes. The external partners will also assist in the advancement of the prototypes through to small-scale production phase.
The envisaged characteristics of the PAF system are that it:

- Is a one or two part system
- Is made from entirely renewable resources
- Is entirely biodegradable
- Offers an impervious barrier to liquids and micro organisms found in everyday use
- Is simple to install- including setting and hardening quickly
- Will be possible for anyone to customise the sub-floor
- Is versatile enough to be used in many climates.

4.2.2 Target Audience and Customer Value Proposition

The benefits to the customer are in design, health and environment. The specific benefits to the market sectors are defined below:

- **Health:** The impervious barrier to water and microorganisms will be essential to the healthcare industry in wet areas to preserve hygiene. Zero VOC emissions and a complete hygienic seal offer health benefits to all, with a reduction in contribution to 'sick-building syndrome'. Immediate health benefits to the user will result from the reduction of emissions to the local environment post-installation. The user will therefore experience a healthier atmosphere resulting in less sick-days and greater well-being.

- **Hospitality and Leisure:** The hygiene of the product is further enhanced by the ease of cleaning, making it ideal for hospitality and healthcare markets. Harsh chemical cleaners are not required, reducing costs and decreasing airborne and physical risks to the vulnerable user. This is of particular advantage to the business customers as there is a reduced risk of accidents in public buildings resulting in financial savings. Brand identity and visual individuality can be expressed with little lead-time to product implementation from design, therefore users will receive the benefit of innovative fashionable designs and visual stimulus.

- **Public Sector:** With the movement of ‘Green Buildings’ into the mainstream (INTEGER, 2005, Curan, 2003), the environmental benefits of PAF will appeal to architects and designers, further promoting Interface’s vision. The health benefits and stability of PAF are particularly welcome to those in the public sector who are vulnerable to litigation (Accident Compensation Information, 2005).

- **Residential:** For the home consumer the increased use of digital photography and home computing will allow personalisation of the sub-floor that cannot be achieved with conventional methods of floor-covering.
- **Exhibitions**: The sub-floor can be customised quickly to adapt to rapidly changing fashions, as well as encouraging the business customer to view the floor as a marketing tool. The floor is simple to install and remove making a quick turn-around possible during changes to exhibitions.

- **In-Store**: The flexible nature of PAF will offer buyers the opportunity to adapt the floor to up to date promotions and store-lay-out. The floor may be used as a guiding tool for the customer to encourage them to visit particular areas in-store.

- **Commercial Office**: Individual personalisation of PAF will enable office-users to adapt their environment to suit their needs quickly. The hygienic nature of PAF and the zero VOC emissions will ensure that the local environment is not compromised by installation, as is the case temporarily during the instillation of some soft floor coverings and industrial flooring systems (Wallace, 1987).

### 4.2.3 Customer Reach

This concept has the ability to penetrate diverse markets, as the product is so versatile and flexible.

This concept will mostly appeal to end-users and designers as it offers full design flexibility with colours, textures, shapes etc. With the increased use of digital photography and home-decorating programs, this concept completes the ‘design vision’ and brings the floor to the forefront as a design tool.

In moving toward a design-upwards system the focus during renovation can change to the floor and consequently its promotion can be increased. This greater awareness will enable Interface to promote its vision through the increased product focus. The flooring will be changed more frequently as it becomes higher fashion. Although the use of material here would increase, it may not be detrimental to the environment as it could be generated from renewables and returned as benign emissions to the earth.

If Interface can develop the residential sector then the end-user awareness can be greatly expanded. The concept will be extremely influential in raising customer awareness of Interface and the 2020 vision of sustainability, since Interface does not currently have a high volume of business to consumer sales.

### 4.2.4 Time To Market

This is estimated at 5-10 Years. This can be estimated from the following time scales.
Phase I: 0-6 months; Concept brief defined, essential partnerships explored and established.

Phase II: 6-12 months Initial prototyping of polymer.

Phase III: 12-18 months Testing of polymers and substrate.
Phase IV: 18 months- 2 years designs. Set of prototypes completed with

Phase V: 2- 4 years Market research, costing, full-scale testing, and small-scale installation leading to one prototype.

Phase VI: 4- 10 years: Small-scale production, costing, full ROI calculations, modification in line with market response continuing to large-scale production.

The first six months of this project was defining the concept brief and establishing partnerships in order to acquire the relevant expertise. Agrotechnology and Food Innovations (A and F) were identified as a leading biopolymer researcher that could provide valuable input to this project.

In order that a prototype could be developed, the second phase of the project was further divided into 4 tasks:

- Translation of the PAF concept into measurable properties
- Proof-of-principle A and F oleochemical binder technology
- Screening of available casting technologies
- Feasibility of other systems

The translation of PAF into measurable properties led to the prototype requirements that are described in the next section (4.3).

The second phase of the project concentrated on the oleochemical binder technology and various other options were suggested as a result of the review that concentrated on possible pourable biopolymer systems. The research also comprised investigating other biopolymer systems, as shown in Chapter 2.

Available casting technologies were examined and a patent search completed to assess if any product currently available fulfilled the prototype requirements. This is shown in the next section.
4.3 Prototyping

4.3.1 Requirements

As previously described, one of the first tasks was to translate PAF into measurable properties in order that the prototypes can be assessed against a standard. It was not intended that the prototype requirements would be those of the product, but rather an intermediate product. This ensures that options remain open for the first stage of this project, as properties can be refined through experimental evaluation and assessment. In order to define the prototype requirements, a number of tasks need first be completed. These are shown in the figure below.

![Figure 1. Inputs required in order to create PAF prototype](image)

Initially the important characteristics were defined as drying time, durability and adaptability. They were expanded into dry to touch after a known time, within a range of peel strengths, and a two-component or thermally activated system, which is translucent, non-hazardous and made from a defined amount of renewable resources. These are defined further for the prototypes below.
The prototype requirements could then be defined with the aid of the knowledge gained from screening of existing casting technologies and reviewing that which is currently possible. The existing technologies examined included epoxy resins, screeds, resin concrete, resin mortar, floor paint, vinyl and carpet tile. The application systems that are frequently used are brush, grooved trowel, spray (pump and aerosol), roller, bucket and shovel.

By screening the existing technologies the range of peel strengths could be defined. The maximum was defined as that of a strong adhesive on prepared concrete—approximately 10 MPa, and the minimum defined as that of a magnetic tile on a prepared screed, which is approximately 0.75 MPa.

An extensive search into the use of biopolymers, (described in Chapter 2), showed that there is little information about pourable biopolymers. Therefore their properties were a secondary consideration as the prototype requirements were reached after major consideration of that required by the flooring market.

No patents were discovered that precluded further development work. Technologies in this area are still developing, and although there are many pourable flooring systems, these are frequently industrial systems based on epoxy resins, concrete or paints, which are based on non-renewable materials and involve complex application methods.

Initially the concept brief set the amount of renewable materials contained in the product to be at 100%. The literature search revealed no liquid biopolymer systems on the market that are 100% renewable. There are some systems currently being investigates for use in the laminates industry based on vegetable oils (Fowler, 2005). However, these are not commercially available and contain a number of hazardous processes such as ozonisation and the use of volatile gases.

The testing of the principal technology is described in section 4.3.2. Based on this initial investigation, which showed that there would be much scope for improvement, and the lack of pourable biopolymer patents, the renewable content of the prototype was set at 50%. Therefore the prototype requirements are a compromise between the ideal and achievable situation.

Based on this search, the prototype requirements were defined as:

1. Dry to touch at 25°C after 6 hours
2. 0.75 MPa < Peel strength on concrete (brushed and set) < 10 MPa
3. Either
   a. Thermally activated system or
b. Optically activated system
c. Several component system with at least one component liquid at 25°C

4. Materials are non-hazardous (in laying/use/disposal)
5. Translucent enough to see clearly the sub floor through a 1cm layer
6. Made from at least 50% renewable materials and no more than 50% non-hazardous materials

Various products in the market place were then compared to the prototype requirements in table 1. These are all industrial systems used in various applications.

Concrex is a tough epoxy resin mortar for repairing concrete floors. Floor paint is used decoratively, although hardwearing and is applied over another flooring, such as concrete. Epoxy gloss paint is generally solvent based and must be applied in well-ventilated areas. Flow Top is a slip-resistant coating, which can be over-coated. It is suitable for use on uneven and damaged concrete to produce a smooth, high strength surface.

Vinyl is the second largest volume plastic produced in the world (Vinyl Info, 2005). It is a flexible floor covering provided in roll or tile form that is glued to the sub-floor. It is hard wearing and offers good flammability resistance.

<table>
<thead>
<tr>
<th></th>
<th>Concrex</th>
<th>Floor Paint</th>
<th>Epoxy Gloss Paint</th>
<th>Flow Top</th>
<th>Vinyl (roll)</th>
</tr>
</thead>
<tbody>
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<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
</tbody>
</table>

*Table 1. Examination of existing technologies compared to PAF prototype requirements.*

These current technologies do not fulfil the PAF prototype requirements and all fail the renewable resources criteria. There are some that can be made from an increased renewable content, but have not reached the mass market. Therefore alternative has to be sought. The oleochemical binder technology as suggested by A and F was initially investigated.
4.3.2 Investigation of a Possible System

This technology is based on an epoxidised linseed oil (ELO) (figure 2) and cross-linker (figure 3) that will form a network as the system cures. This results in the biopolymer, shown in figure 4.

Figure 2. Simplified chemical structure of ELO

Figure 3. Cross-linker formed by heating di-ether in the presence of moleic anhydride

Figure 4. Cross-linker and ELO react to form polymer

This polymer was investigated principally by using different ratios of cross-linker to ELO. A change in ELO:Cross-linker ratio from 1:5 to 1:3 resulted in an increased tear dry time from 15 to 24 hours, but a lower full dry time. This alteration also resulted in a decreased maximum stress, glass transition temperature and Young’s Modulus, with an associated increase in strain at failure. Table 2 shows the variation in these properties that also occurs with curing temperature.
A 6-speed elcometer drying time recorder was used to assess drying time. This has been used extensively in the paint industry to assess drying time of coatings. British Standard EN 29117 describes a drying test using plungers, on which the drying time recorder is based. However, since this equipment was not readily available, the drying time recorder is used as a guide.

A ball tip is placed into the coating and the recorder begins to move this ball at a predefined speed. As the coating dries, the trace left in the coating by the ball identifies each stage of the cure. Initially the coating levels off under gravity. Once it begins to cure, a thin, dry film appears on the surface and so the ball leaves a trace. The coating continues to dry, and finally, after a period of time, the coating is totally cured (Elcometer, 2005). Figure 5 and table 2 show the results below.

![Figure 5: Variation of curing time at room temperature, measured using a drying time recorder, in comparison to molar ratios of ELO/Cross-linker](image)

<table>
<thead>
<tr>
<th>Ratio</th>
<th>ELO:Cross-linker</th>
<th>Curing Temperature (°C)</th>
<th>Curing Time</th>
<th>Stress-max (N/mm²)</th>
<th>Strain at Fracture (%)</th>
<th>Tg (°C)</th>
<th>Young’s Modulus (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1:5</td>
<td>22</td>
<td>3 days</td>
<td>0.5</td>
<td>40.6</td>
<td>-4.4</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>1:3</td>
<td>22</td>
<td>3 days</td>
<td>0.4</td>
<td>32.3</td>
<td>-9</td>
<td>0.8</td>
<td></td>
</tr>
<tr>
<td>1:5</td>
<td>150</td>
<td>30 min</td>
<td>1.4</td>
<td>51.7</td>
<td>6.2</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>1:3</td>
<td>150</td>
<td>30 min</td>
<td>3.5</td>
<td>63.1</td>
<td>14.7</td>
<td>6</td>
<td></td>
</tr>
</tbody>
</table>

*Table 2: Variation of mechanical properties tested at room temperature with curing temperature and molar ratio*
These mechanical tests are not conclusive as they were conducted only to give an indication of properties. They were performed on a Zwick Mini Hasy System at A and F. It is recommended that these tests be repeated in a controlled environment in order to achieve consistent results.

The mechanical properties were tested three days after the reaction had begun to occur at room temperature. It may be that the reaction is still occurring, albeit very slowly. Therefore these tests should be repeated several times after reaction begins. It is recommended that they are repeated several days, weeks and months after the two components are mixed, and after aging tests under increased temperature and UV light. This will be expanded upon when the next stage of the project is defined further.

However, as previously stated, these tests were designed to give an indication of mechanical properties and can therefore be used as a guide to performance. The conclusion that can be reached is that these polymers are rubber-like in their performance, with low Young’s Modulus and high strain at failure. This is advantageous at this stage in the development of PAF as the material can resist impacts and properties can be further modified at a later stage.

The main drawback with this system is its curing time of over 50 hours. As a first step to reducing this, catalysts were introduced at 1 wt% in order to assess if a reduction in curing time could be achieved. The results of adding three catalysts to the molar ratio 1:3 are shown in figure 6.

1 wt% would give a good initial indication of catalyst effect, although different amounts should also be investigated as part of the second stage of this project. Manganese is known as a surface dryer (Hardy, 2004), whereas tin and zinc are used in the form of salts in order to increase electron transfer during reaction. It may be that the manganese dries a thin coating quickly (as is shown by the drying time recorder), but does not work as effectively for thick coatings, which may be laid down as PAF (Hardy 2005).
Figure 6. Showing variation of curing time with the introduction of catalysts to the 1:3 ELO:Cross-linker ratio mix

These initial experiments showed that the curing time could be reduced by around 20 hours as a first attempt. Although this is dramatic, this requires further investigation, in order to verify the effect of differing the amount of catalyst, as there may be environmental factors that limit their use.

An important next step for this investigation is to consider the effects of different amount of catalysts on the reaction rate. There are also a number of other catalysts to consider, such as sulphuric acid and sodium hydroxide. Although these are not considered environmentally friendly, they may provide some indication as to how fast the reaction could occur at room temperature and effect on mechanical properties. This would give us more insight into the reaction. If it is found that the curing time cannot be improved, even with these powerful catalysts, it is unlikely that the other catalysts will be able to improve it to the prototype properties required.

This initial investigation has shown that there are a number of possibilities for this particular system. However, there are other systems that may be worthy of investigation. These are described in the further work.
4.4 Future Work

Although this system of epoxidised linseed oil and cross-linker has shown a great deal of promise as a material for PAF, there are other cross-linkers and oils that require consideration. There have been described (Boquillon, 2000) a number of cross-linkers that can work with ELO to create a polymer. These are heated at 150°C in the same manner as the cross-linker previously described. They are listed and shown below.

<table>
<thead>
<tr>
<th>Name</th>
<th>Formula</th>
<th>Molecular weight (g/mol)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phthalic anhydride (PA)</td>
<td><img src="image" alt="Phthalic anhydride" /></td>
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</tr>
<tr>
<td>Cis-1,2,3,6-Tetrahydrophthalic anhydride (THPA)</td>
<td><img src="image" alt="Cis-1,2,3,6-Tetrahydrophthalic anhydride" /></td>
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</tr>
<tr>
<td>Methyl-tetrahydrophthalic anhydride (MTHPA)</td>
<td><img src="image" alt="Methyl-tetrahydrophthalic anhydride" /></td>
<td>166</td>
</tr>
<tr>
<td>Methyl-hexahydrophthalic anhydride (MHHPA)</td>
<td><img src="image" alt="Methyl-hexahydrophthalic anhydride" /></td>
<td>168</td>
</tr>
<tr>
<td>Methyl-endomethylenetetrahydrophthalic anhydride (METH)</td>
<td><img src="image" alt="Methyl-endomethylenetetrahydrophthalic anhydride" /></td>
<td>178</td>
</tr>
</tbody>
</table>

*Table 3. Cross-linkers that may be used to form a polymer with ELO*

These cross-linkers have been used with epoxidised linseed oil and basic catalysts (Boquillon, 2000) and are mixed and heated to 145°C for 15 minutes to cure. Although they are solid at room temperature, they could be dissolved in solvents for application. This may not environmentally preferable as the cross-linkers and solvents must be chosen and investigated carefully.
Although the future work will concentrate on the primary system, there is some scope for investigating other options. The following series of experiments will be conducted into varying the amount and type of crosslinkers and catalysts.

The ratio of ELO:cross-linker will be varied within the limits previously used from 1:5 to 1:1 in increments of 0.25. There will also be extreme measurements conducted with both the catalyst and cross-linker in extreme excess. It is suggested that from 1-10 wt% of catalyst is first used in increments of 1 wt%. Once this has given an indication as to the ideal amount of catalyst for the system, these experiments will be combined in order to establish the ideal mixture of all components.

There are several catalysts that have been suggested and these will also be examined by varying the amount and type of catalyst. If the system does not show promise at this stage, the cross-linkers will be altered to determine if these can be more effective at the same ratios.

A suggested project plan for the next six months is shown below.

![Gantt chart showing suggestion for next 6 months of PAF work](image)

**Figure 7. Gantt chart showing suggestion for next 6 months of PAF work**

At the end of the six months work, it is suggested that the next phase is ended and assessed again. It may be that at this point another alternative technology becomes more favourable as it becomes apparent that this technology is unfeasible.

Detailed plans for the next 6 months, and outline plans for the subsequent 2 years are set out in the next chapter.
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Dianne Carter

24-Month Report

01.04.05 - 01.10.05

"Towards Sustainable Design and Manufacture of Textile Flooring Products"
Abstract

"The aims of the project are to develop innovative materials and flooring to migrate the textile flooring products towards the company’s vision of sustainability. This will involve a holistic consideration of the supply chain from sourcing renewable raw materials, improving/re-engineering production processes, refurbishment, recycling, downcycling and disposal."

A review of current material and processes at Interface shows that many of the materials employed are unsustainable and hence do not fit with the company’s 2020 vision.

Natural raw materials have been reviewed as alternatives to the petrochemical-based feedstock used currently in the manufacturing process. These have been readily available for a number of years, they have been tested extensively and the technology exists to facilitate their use. However, performance has proved critical within the flooring industry and therefore a more refined feedstock is required for use within current products and innovative flooring concepts.

The preliminary part of the EngD project was to evaluate the current methods of manufacturing carpet tiles and assess where obvious reductions in environmental impacts could be made. Carpet tiles comprise of a face yarn and a backing system that contains, by weight, 3% fiberglass, 1-2% fleece and over 95% bitumen mix (comprising 33% pre-modified bitumen and 67% limestone filler). A significant increase in recycled content of the product can be achieved by replacing the greatest ingredient by weight i.e. the limestone in the backing, with recycled material that is currently diverted to landfill. The 12-month report described the increase of recycled constituent by replacing this limestone filler

This report describes the initial investigation into the use of a bio-resin based on renewable oils. There are many opportunities that are becoming clear for the use of the material within both Interface Europe and the market for interior furnishings. These are described within the further work section.

In order to investigate the use of this material within other flooring concepts, the relationship between consumer and flooring was examined. The concepts were then evaluated against these requirements and several have been taken further within the business. Two of these concepts are described and explored as Pour-A-Flor and ‘Sustainable’ Interlock.
‘Sustainable’ Interlock uses the bio-resin within a tile system and has been chosen as the project to be investigated through the next phase of this project. The future work section shows that the further work will be sub-divided into several sections. These include materials selection criteria, materials testing, feedback and testing of several flooring systems.

This project will ultimately result in a new flooring system, suitable for use as resilient flooring but with reduced environmental impacts over its lifetime in comparison to the product currently being manufactured by Interface.

The material used for this system also shows potential for use elsewhere within the company. Therefore this project may have more wide-reaching implications for the business and increase the circle of influence surrounding the story of sustainability.
1. Introduction

Background to the Carpet Making Industry

In order to understand the context of this Engineering Doctorate project, a background to the carpet making industry must first be established. This chapter will then introduce Interface Inc. and their role in establishing a more sustainable industry. It will be shown that although great progress has been made in the last ten years, there is still more work to do.

The carpet making industry has its origins around 4,000 years ago in Egypt, Mesopotamia and the Middle East. The oldest known rug discovered was from around 400 BC, known as the Pazyryk carpet (Huntington, 2005). The industry has evolved from home weaving, through the industrial revolution to woven and then tufted carpets. Today the carpet industry is worth around US$25 billion at the mill level annually (CRI Sustainability, 2001).

Carpet tiles now comprise approximately 40% of the soft flooring purchases for the contract market in the UK. It is estimated that 73,000 tonnes of non-renewable materials are consumed by this industry and 5,800 tonnes of industrial waste produced per annum (Anderson, MCC, 1998).

A carpet will typically be composed of a face yarn, primary backing, a bonding compound and often a secondary backing (Figure 1).

![Figure 1. Typical cut pile carpet profile](image-url)
Figure 2 shows that in 2003, 96% of the carpet fibre produced in the United States was petrochemical based. Nylon has become used in such large quantities as it offers low cost, excellent wear resistance and abrasion resistance.

![Pie chart showing fibre consumption in the US by weight (The Carpet Primer, 2003)](image)

*Figure 2. Annual fibre consumption in the US by weight (The Carpet Primer, 2003)*

It was not always the case that nylon was used so extensively. Wool was the traditional material used in carpet manufacturing, as it was cost effective and readily available from local renewable resources.

In the 1960s viscose became more fashionable and was tried as a cheaper alternative to wool. However, in comparison to its natural counterpart, its wear properties were poor, the yarn tended to flatten and it burned easily (Colton, 2004).

Nylon was subsequently added to wool within yarn systems, typically at 20% by volume. This increased durability considerably, whilst retaining a similar feel (CRI Primer, 2003). For example, wool carpet typically survives 7–9,000 revolutions of an abrasion machine (BS EN 1813:1998), whereas a 20% nylon addition increases the survival to 30–50,000 revolutions (Nunney, 2004).

The simultaneous growth in the plastics, petrochemical and oil industries during the mid twentieth century resulted in a vast reduction in cost and a consequential boom in the use of plastics (Subramanian, 2000). In addition, wool requires a great deal of processing such as scrubbing, combing etc. and can only lend itself to yarn spun from staple fibre. By contrast, synthetic fibres can be staple or continuous. Continuous filaments have the benefits of being cheaper to process and cause low off-quality levels.
Hence, the use of nylon began to increase considerably within the carpet industry, at the expense of natural materials such as wool for which use declined to the lowest point ever.

There have been attempts within the industry to reintroduce natural materials, increase recycled content, reduce waste, increase renewability and generally reduce environmental impacts. There are minor companies that offer a variety of floor coverings containing a quantity of natural materials. Those most often included are wool, jute, hemp, fiscal, cotton, wood, silk, linen and bagasse (Geosites, 2003). However, these have remained relatively small-scale operations and the use of these products has generally been limited to the residential market. These materials are discussed further in chapter 2.3.

1.2 Interface Inc. and Sustainability

1.2.1 Global Progress

In 1995 Interface Inc. sold $802 million worth of carpets, textiles, chemicals, and architectural flooring. In order to achieve this, the company, along with their suppliers extracted 2.69 million tonnes of material from the Earth's stored natural capital. Of this, 880,000 tonnes was relatively abundant inorganic material, mostly mined from the Earth's crust and 1.76 million tonnes originated from petrochemicals. Roughly two-thirds of these petrochemicals were burnt up in order to convert the remaining third and the inorganic material into products (Anderson, MCC, 1997).

In 1994 Ray Anderson set out his vision of sustainability for the company he founded in 1973. He challenged his associates "to be the first company that, by its deeds, shows the entire industrial world what sustainability is in all its dimensions: people, process, product, place and profits- by 2020- and in doing so we will become restorative through the power of influence".

Sales at Interface Inc., ten years later, now stand at around US$1 billion. However, carbon intensity is down by a third, greenhouse gases are down by 46% in absolute terms, despite the increase in product volumes, and water usage has been reduced by 78% per square metre of product (Anderson, 10th Anniversary message, 2004).

Interface Inc. has therefore made considerable progress in addressing the environmental issues faced by the carpet industry. Even just by using carpet tiles, the main product of Interface Inc., installation waste can be reduced by 67% (Interface, Why Modular?, 2003).
Interface Research Corporation (IRC) in the US is intended to support this vision by providing basic research and technical support to all the Interface subsidiaries worldwide, providing leadership in the development of socially sustainable practices and developing newer and more environmentally friendly technologies, process and products towards the goal of sustainability.

However, traditional research also requires innovation. Therefore a recent development has resulted in the creation of a Global Innovations Group. This group has responsibility for inspiring and exploring innovations, partnerships and concepts to support the global sustainability initiative.

1.2.2 Progress Within The UK

Interface Inc. is the largest manufacturer of carpet tiles globally and Interface Europe manufactures 24% of the carpet tiles for the contract market in the UK and Ireland, producing over 3.6 million square metres per annum.

Interface Europe has focused on reducing waste, reducing water usage, reducing energy requirements and the use of 100% renewable energies throughout the UK, in line with global achievements.

There has also been the introduction of Cool Carpet, the industry's first climate neutral carpet. The level of greenhouse gas associated with the life cycle of the carpet, expressed as CO₂ equivalent, is offset through investment in projects that reduce or reverse the impact of those emissions (Interface, Cool Carpets, 2005).

Interface Europe has made similar progress to Interface Inc. in tackling the seven fronts of sustainability as they have defined them; eliminating waste, having only benign emissions, using renewable energy, closing the loop to use recycled or bio-based materials, using resource-efficient transportation, sensitising stakeholders and redesigning commerce.

It is clear that closing the loop is one issue that can be more easily and quickly addressed when the materials used in the product are assessed. This would be a further step on the way to sustainability.

1.3 Project Aims and Structure of This Document

This project began by analysing the constituents of a carpet tile and assessing the way in which these could be altered to facilitate a more sustainable product. Interface identified, as a first consideration, the introduction of recycled or renewable materials.
There has been a continuing need to introduce a greater amount of recycled material within UK products. This situation was primarily addressed by an investigation into the filler that makes up a majority of the product. The results of this investigation that intended to increase recycled content of the product to 70 wt% are described in Appendix A.

This report also describes alternative methods of providing a flooring product than that which is currently offered by the carpet tile, manufactured from mostly petrochemical feedstock.

There are other feedstocks that have arisen during the course of this investigation to be considered for use in UK manufacturing sites, such as renewable materials, and these are described in Chapter 2. These may be designed to replace the components of a carpet tile or may be used in other innovative concepts. Chapter 2 also describes the perceived and actual barriers to their use.

Other methods of offering flooring to those existing products are described in Chapter 3. These innovative concepts may be able to make use of these renewable materials to offer a similar service in practice, without compromising performance. These concepts are known as ‘Pour-A-Flor’ and ‘Sustainable’ Interlock and can be based upon a resin manufactured from renewable resources.

Chapter 4 describes the future work that is required to progress ‘Sustainable’ Interlock towards a prototype. This project would result in the replacement of PVC with a material that is of lesser environmental impact.

This report concludes with a projected plan for the next 2 years.

The aim of this project is to produce an alternative method of providing all the services that current flooring offers, with a reduction in overall environmental impact over the entire life cycle.

This project would facilitate the move towards sustainable production by introducing recycled and renewable material into current products. This project also aims to further research into novel renewable systems so that they may be used in novel flooring systems in the future.
2. Renewable Materials

2.1 Introduction

The basic construction of carpet has been outlined in the previous chapter. However, in order that carpet tiles can be placed directly on a sub-floor and offer dimensional stability within a range of humidity and temperature, a backing is required. The constituents of the backing are examined here.

This chapter describes the materials currently used for carpet tile construction and makes the case as to why they cannot continue to be used in a sustainable company.

There are several options for replacing this material and in this chapter two of these options are explored – replacing constituents with recycled material and replacing constituents with renewable material.

2.2 Carpet Tile Manufacture

This section describes the materials that make up the carpet tile backing and the proportion of environmental impacts they contribute in comparison to the entire life cycle of the tile. First the carpet tile construction will be examined and evaluated.

When constructing a carpet tile from a tufted piece of cloth, a pre-coat is applied first to hold the fibres in place, followed by gradual build-up of a complete backing system. The end result is that the backing contains, by weight, 3% fibreglass, 1-2% polypropylene fleece and over 95% bitumen mix (consisting of 33% bitumen which has been modified for this use and 67% limestone). The bitumen mix is applied hot and cooled to allow it to set and bind the other elements together.

Figure 1 shows the resulting construction made up of these constituents.
There are inherent problems with each of the components such that they cannot participate in a sustainable product.

Although it constitutes little of the weight of the backing, there are concerns for health and the environment during the manufacture of fibreglass (Hesterberg, 2001). It also has high environmental impacts as it is manipulated through a great deal of energy-intensive processes (Krivtsov, 2004). There are natural materials that can offer dimensional stability, such as jute fibres in a rubber matrix (GRC, 2005); however, these are bulky and currently not cost-effective.

The fleece is made from polypropylene, manufactured from petrochemicals, as is the bitumen: i.e. they are unsustainable in the long-term. There are other alternatives that may be sought, however, such as a natural fibre instead of the fleece. Replacing the bitumen as a cheap, easily manipulated rubber-like substance is more problematic since the purpose of this material is to form bulk at a cost-effective level. Natural rubbers that may be used are higher cost in general (Highway Maintenance, 2005).

The limestone is quarried from a local source and is unsustainable. This is the constituent that may offer the easiest substitution, as its role is simply to provide bulk as inert filler.
If the supply chain of the carpet tile is examined, it can be shown that the greatest environmental impacts arise from the embodied energy in nylon used in the face yarn. Although it contributes only 8% of the embodied mass, it contains 38% of the total embodied energy and contributes 49% to the global warming potential (GWP) (Interface LCA, 2002).

Life cycle analyses show that the large amount of processing is an important factor in the environmental burden of the carpet tile, although it is dwarfed by the environmental impacts of the petrochemical-based materials. Examining the GWP only, the distribution of impacts is virgin raw material impacts, 71%, energy in manufacture, 16%, transportation, 1%, use, approximately 3% and end-of-life, approximately 9% (Interface LCA, 2002).

It can therefore be seen that although substituting some of the backing material with a recycled alternative can make easy gains, replacing the nylon with a material having lesser environmental impact would be the real advance.

It is also worth noting that some attempts have been made at dematerialisation. The non-renewable material required to make one unit of product has been reduced by around 40 wt% in the last 7 years (Interface Sustainability, 2005). This has reduced the net inputs required and consequentially reduced environmental impacts.

A breakthrough carpet tile has been developed at Interface based on the concept of biomimicry- the idea that natural systems can guide the design of man-made products (Benyus, 1997). Typically carpet tiles have to be laid in a predefined pattern to achieve the desired visual effect, creating small amounts of edge waste. “Entropy” carpet tile is laid randomly and therefore provides near-zero installation waste.

The Entropy range has also lead to the “Inspiration Squared” range which comprises a wide range of designs, also based on biomimicry but incorporating contemporary styles. Using this type of tile can extend the lifestyle of the installation, as tiles can be interchanged when different traffic areas exhibit different wear rates.

RE:Entry is the name given to tiles that have been returned to Interface, refurbished and then donated to non-profit organisations (Interface website, 2004). Since 70% of carpet is discarded because of colour concerns, this is a route worthy of consideration (Color Your Carpet, 2001).
It has been shown that Interface has made a number of steps towards redesigning the use of flooring in order to reduce the volume of material required to perform the same function. However, as previously discussed, the material itself must also be altered or substituted to become more sustainable and make progress towards the 2020 vision.

2.3 Introduction of Recycled Feedstock

2.3.1 Introduction

A natural first consideration in reducing environmental impact is to use recycled feedstock, given that:

- Customer satisfaction is of utmost importance
- Performance is critical
- It is costly to alter capital investment in process machinery,

Although this will not produce a fully sustainable material, it can reduce the total amount of raw material and energy required during a life cycle.

Replacing material within a carpet tile with recycled alternatives will not yield a solution to the 2020 vision, but will provide a step on the path. This section describes two recent attempts to introduce recycled feedstock— that with greatest contribution to GWP throughout the life cycle and that with greatest contribution by weight.

Although achieving sustainability means much more than offering recycled products, along with renewable materials, it is one of the most visible means of communicating the sustainability message.

2.3.2 Face Yarn

LCAs show that one of the greatest environmental impacts of a carpet tile arises from the embodied energy in the nylon face yarn (Interface, LCA, 2002). In order to achieve the greatest single reduction in GWP, whilst retaining performance, the face yarn can be replaced by recycled material.

There have been attempts within the larger polymer producers such as DuPont (Plastics Resource, 1999) to produce recycled nylon yarns. The recycled content will vary dependent on yarn type and colour.
Recycled yarn comprising at least 80% post-industrial waste has so far been introduced within 18 product types at Interface and reductions in overall environmental impacts are being achieved.

2.3.3 Backing System

The greatest increase in recycled content in the product can be achieved by replacing the greatest ingredient by weight- limestone. This material is mined and used as virgin aggregate material, i.e. it is used without further processing (Environment Council, 2005).

If this feedstock can be replaced and used in conjunction with recycled yarn there will be an increase to nearly 70 wt% recycled content from the current recycled content of zero in many products.

The introduction of replacement feedstock was investigated as part of the present work. A full report is given in Appendix A. The main results are outlined below.

The characteristics of existing and replacement feedstocks needed to be compared carefully in order that new materials could be introduced with no compromise in performance, both in production and use. The existing virgin material, of known and consistent characteristics, was causing the processing line to run below optimum speed. Therefore an investigation of this problem and a solution was required first before a recycled alternative could be introduced.

The initial investigation examined bottlenecks in the transport of material from storage to the processing line. The underlying causes of the bottlenecks were identified and solutions implemented such that a constant line speed improvement of some 25% was achieved.

The recycled feedstock was assessed for parameters affecting flow, such as particle size, shape and composition. These data, combined with the increased confidence in processing, allowed full-scale trials to be carried out which demonstrated that an acceptable line speed could be maintained using this recycled feedstock. These experiments also indicated the range of properties that would be required in other recycled feedstock.

This result means that the virgin feedstock can be substituted in the process with confidence in the machinery, process and method. As a consequence the substituted material could be from a recycled source, and when used in conjunction with Interface's recycled face yarn this results in an immediate increase to over 70 wt% recycled product content.
The recycled feedstock is now being used for long-term full-scale process trials with a view to including this material in every tile produced in the UK in the near future.

This work has begun to address the need for recycled content. However, materials derived from renewable resources have the potential to decrease environmental burdens even further.

2.4 Introduction of Renewable Materials

2.4.1 Introduction

In using recycled materials, there are a number of processing steps required to achieve a workable feedstock. An alternative to using recycled material is to use one that minimises processing in order to minimise environmental impact. Natural raw materials may require little processing to achieve an effective material.

Raw materials may also be processed through a greater number of steps to produce a wider range of products with increased performance and greater range of properties. These are described in this section and have already been used within Interface.

2.4.2 Natural Raw Materials

Introducing natural raw materials into a product are an obvious choice for reducing environmental impact. However, traditional flooring products made from these sources generally do not pass the same performance criteria that their petrochemical counterparts do. For example, wool carpet typically survives 7-9,000 revolutions of an abrasion machine (BS EN 1813:1993), whereas a 20% nylon addition increases the survival to 30-50,000 revolutions (Nunney, 2004).

Natural fibres can be derived from many sources, e.g. extracted from the leaf, the inner bark, fruit, seed, animal wool or hair and insect cocoon. Fibres are used to form into threads, yarns and ropes that may be woven into tapes or fabrics. One significant drawback with natural fibres produced in this manner is that properties vary from crop to crop and depend on seasonal variations.

Natural fibres generally have lower tensile strengths, elongation to failure and durability than the nylon fibres that are used typically in textile flooring (DTI, 2003). However, if properties could be improved and made more consistent then they could be integrated into wider markets. There are niche markets that make use of these materials (Geosites, 2003).
Natural fibres such as wool and hemp are not generally used in the heavy contract category, such as that used for commercial offices, as they cannot pass the stricter performance criteria due to their inconsistency in properties and their lower material properties. However, there are other renewable feedstocks that remain to be considered for use in industrial applications and these will be discussed in the next section.

2.4.3 Processed Renewable Materials

There are a large variety of feedstocks still to be considered for replacing material within carpet tiles. The potential for the use of recycled material and natural raw materials have already been discussed.

There are however other materials that may be useful substitutes for the materials currently in use. These include processed renewable materials such as bio-based polymers, modified plant tissues, modified natural chemicals, water-soluble polymers and modified naturally occurring waxes. The manufacture of these materials includes a greater number of processing steps. This processing is less desirable than using raw materials in their natural, or near-natural, state as more energy is generally used and the length of the supply chain from producer to consumer is increased.

Bio-based polymers are still developing but have been used for a number of years. Since the 1990s polymers based on renewable feedstocks and natural fibres have been used in a variety of applications, such as biodegradable capsules for drug delivery systems (PURAC, 2004), non-woven material in the replacement of human tissue (Eagles et al, 1997), waste bags and packaging material (Van de Velde, 2002).

The main driver for the increased use of processed material based on renewable feedstock has been environmental superiority in terms of a reduced overall environmental impact. An important secondary impact was often their biodegradability. These factors may be expected to continue to drive their development, as they cannot currently compete in many other features. Volume and consequently research investment are still small and therefore they cannot compete on a cost-only basis. Biopolymers (those made from mostly annually renewable resources) made up less than 2% of the plastics market in the EU in 2001 (ERRME, 2001).

Life cycle analyses have been carried out that show that polymers based on renewable feedstock are generally better overall than their petrochemical based counterparts (Patel et al, 2003). As an example, Starch polymer pellets require 24-75% less energy than polyethylene pellets and GWP can be 20-80% lower.
However, there are many more factors to consider in making the choice to go from non-renewable to renewable resources such as transport of raw material, genetic modification (GM) issues and localised social impacts. The transport issues can be great as unprocessed biomass is generally bulky and the end product of low volume in contrast to the small size of petrochemicals with a ready network of transportation. GM has been an issue at the forefront of European matters (IsiS, 2005, BBC, 2000 and UK Environment, 2005) and is viewed with suspicion by the general public. Social impacts can be great in localised environments as potential food crops are substituted for those crops that can be sold further afield at a premium (CIGB, 2005).

Even given these concerns, commercial biopolymers have recently found use in a wide variety of applications such as polylactic acid (PLA) used as face yarn in carpet tiles (Interface, 2003), EverCorn Resin™ used in drinks containers (Japan Cornstarch, 2005) and even another starch based polymer, Materbi™, used in dog toys (Novamont, 2005). Biopolymers are used in adhesives, fibres, animal products, personal care, medical, garden and more commonly packaging applications (Biopolymer.net, 2005).

The processing of biopolymers can restrict their applications to those that are thermoformed since a number cannot be formed into films without purification steps during extraction. However, the primary concern when considering biopolymers as part of a flooring system is the material properties. The material must be fit for the purpose for which it is designed.

2.5 Conclusion

A variety of materials have been discussed in this chapter, many of which have the potential to replace those currently in use within the carpet tile construction. However, there are many barriers to their use, such as performance, consistency and reliability of feedstock, ability to process a number of forms and cost. Many of these drawbacks are actually imagined, as the carpet tile is engineered to give better performance than that which is sustained in practice.

These obstacles are often restricted to the use of the current method of constructing a carpet tile. There may be alternative ways of offering flooring without this type of construction. Alternative flooring may therefore be able to use renewable materials and processed renewable materials without compromising performance or perceived performance. This will be discussed further in the next chapter.
3. Sustainable Innovation

3.1 Background

The previous chapter described the difficulties with maintaining the traditional carpet construction, whilst trying to vary the constituents such that they become more sustainable. There may be other methods of offering flooring that could be environmentally preferable, which are not currently in the marketplace. This requires a novel approach to designing flooring systems within Interface Europe.

The Process Materials Research (PMR) group at Interface has responsibility for generating new flooring solutions, focused to date on the traditional carpet-manufacturing methods. The PMR Manager has ultimate responsibility for agreeing projects, setting objectives and a project leader for these types of projects. In parallel with the PMR group a new role of Innovations Director was recently created, directly reporting to the Senior Vice President, Central Marketing. This role has responsibility for bringing an Innovations Pipeline of ideas and products to completion.

As part of this new brief, on the 12th and 13th May 2004 Interface Europe facilitated an Innovation Workshop with a number of experts, repeated on 25th and 26th May 2005. The principal aim of these workshops was to formulate new ideas for the floor coverings and interiors market based on “the principles of sustainable living and restorative behaviour.” The experts were from a wide range of experience and backgrounds designed to give a good mixture of ideas and creative inputs. There were people who describe themselves as sustainable thinkers, textile technicians, marketers, consultants, sustainable designers, academics, mathematicians and engineers.

Day one of the first workshop began with an introduction to Interface and the company’s 2020 vision. A debate regarding the challenges laid out with a view to build preliminary concepts on the future state of working and living spaces followed.

A number of new concepts for redesigning flooring for Interface to develop were suggested. One concept was described as ‘Pour Man’s Floor’ - a fluid biopolymer flooring that is entirely biodegradable.

This concept was developed until it became known as Pour-A-Flor (PAF) and is defined by the fuller “Concept Description” in section 3.2.
At the second workshop some of the concepts were fed back to the participants. Responses and comments were returned regarding how they had been developed which was in turn fed back into the projects. For PAF the suggestions included incorporating only renewable particles to provide the design features and perhaps creating an intermediate product. The initial concept description is described in the next section.

3.2 The Pour-A-Flor Concept

3.2.1 Concept Description

The following section describes the ideal characteristics of the Pour-A-Flor system. The concept is positioned at the top of the waste hierarchy in that it generates no waste at installation, is made from renewable resources and is entirely biodegradable. The material taken from the Earth when PAF is made is returned in a usable form.

PAF is a multipart and modular system. The concept offers flexibility with creativity as the floor is literally poured either onto an existing surface or a new design. PAF is a design-upwards system, in that it encourages the customer to begin creating a room from the base upwards and consider the floor as a major design tool.

The underlay, or design substrate, that constitutes the design offers a range of possibilities. This provides the visual mood for the surface as it provides design flexibility in colours, shapes, patterns and brand identity. Interface would suggest design ideas and sell templates for use within PAF to encourage individual customer creativity, whilst highlighting other areas of sustainability.

The top surface for PAF will be provided in a one or two-part system that can be purchased off-the-shelf as a liquid. The floor will be designed to set-to-touch quickly (2 hours maximum) and to harden for contract use within a designated time (6 hours maximum). The PAF will be self-levelling and offers a hygienic seal for the floor, whilst incorporation anti-slip elements, which will be designed to be an impervious barrier to water and microorganisms, so making PAF ideal for wet areas.

The floor is easy to clean, as the surface can be rough or textured (through the addition of particles into PAF), but unlike textile surfaces. The surface can be vacuumed and mopped using conventional methods without damage to the surface.
PAF can be removed from the substrate and the biodegrading initiated through the application of a 'remover'. This could be composted in-situ or in a designated composting facility without the need for further treatment by over 90% in 90 days as defined by ISO standards 14852:1999, 14851:1999 and 13193:2000 (Murphy, 2004).

Collaborations and partnerships were essential to the success of this concept. Interface required external partners to provide technical assistance to provide initial biopolymer material. Technical assistance is now required from academic partnerships to assess the structure and surface chemistry of the prototypes. The external partners would also assist in the advancement of the prototypes through to small-scale production phase.

In summary the ideal characteristics of the PAF system are that it:

- Is a one or two part system
- Is made from entirely renewable resources
- Incorporates other material as a sub-floor to provide designs that will be possible for the home-user to use
- Is simple to install- including setting and hardening quickly
- Offers an impervious barrier to liquids and micro organisms found in everyday use
- Is easy to clean
- Is versatile enough to be used in many climates.
- Is entirely biodegradable

The concept description shown above is an ideal situation that would require years of research and development in order to move to production scale (section 3.2.4). The first six months of this project were spent defining the concept brief and establishing partnerships in order to acquire the relevant expertise. Agrotechnology and Food Innovations (A and F) were identified as a leading biopolymer research organisation that could provide valuable input to this project.*

In order that a prototype could be developed, the second phase of the project was further divided into 4 tasks:

- Translation of the PAF concept into measurable properties

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* Agrotechnology and Food Innovations describe themselves as specialists in market-driven research for the food sector and agrotechnology. It is a modern research and development facility, focusing on the entire supply chain and works in partnership with Wageningen University. Its key activities are in bio-based products, quality in the supply chain, food quality, agrisystems and the environment. It can offer research facilities that range from the lab to pilot-scale facilities.
• Proof-of-principle A and F oleochemical binder technology
• Screening of available casting technologies
• Feasibility of other systems

The translation of PAF into measurable properties led to the prototype requirements that are described in the next section (3.2.2).

The second phase of the project concentrated on the oleochemical binder technology, suggested by A and F and based on their expertise and strengths.

Available casting technologies were examined and a patent search completed to assess if any product currently available fulfilled the prototype requirements. This is shown in the next section.

3.2.2 Prototype Requirements

The PAF concept was translated into measurable properties in order that the prototypes could be assessed against a standard. It was decided that an intermediate would be an acceptable option on the path to fulfilling the prototype requirements, providing that the intermediary can, in turn, be improved. This ensured that options remained open for the first stage of this project, as properties could be refined through experimental evaluation and assessment. In order to define the prototype requirements, a number of tasks were first completed. These are shown in the figure below.

![Diagram of prototype requirements](image)

*Figure 1. Inputs required in order to create PAF prototype*
Initially the important characteristics were suggested to be drying time, durability in service and adaptability. They were expanded into the following requirements, which were further defined in the prototype requirements:

- Dry to the touch after a known time, i.e. cured sufficiently to touch, but not enough to undergo typical use conditions such as the use of a castor chair
- Within a range of peel strengths, i.e. the amount of force required to peel the material off of a substrate is defined
- A two-component, thermally activated or UV cured system
- Translucent enough to observe the sub-floor through a defined layer of material
- Non-hazardous
- Made from renewable resources - the amount to be defined in the next step

The prototype requirements could then be defined with the aid of the knowledge gained from screening of existing methods for casting floors and reviewing that is currently possible. The existing technologies examined included epoxy resins, screeds, resin concrete, resin mortar, floor paint, vinyl, linoleum, marmoleum, cork, laminates, rubber, mosaic, hardwood, carpet and carpet tile. The application systems that are frequently used are brush, grooved trowel, roller, spray (pump and aerosol), bucket and shovel.

By screening the existing technologies the range of required peel strengths could be defined. The maximum was defined as that of a strong adhesive on prepared concrete- approximately 10 MPa, and the minimum defined as that of a magnetic tile on a prepared screed- approximately 0.75 MPa.

No patents were discovered that precluded further development work. Although there are many fluid-flooring systems, these are frequently industrial systems based on epoxy resins, concrete or paints, based on non-renewable materials and involve complex application methods. This search showed that there is mostly professional competence required to apply these fluid systems and therefore some simplification of the system is required. These systems should be taken into consideration as they could provide further assistance when determining storage and application methods and also may provide a test ground for PAF.

The concept description set the amount of renewable materials contained in the product to be at 100 %. The literature search revealed no liquid biopolymer systems on the market that are 100 % renewable. There are some systems currently being investigated for use in the laminates industry based on vegetable oils (Fowler, 2005). However, these are not commercially available and involve a number of potentially hazardous processes such as ozonisation and the use of volatile gases.
The prototype requirements are a compromise between the ideal and achievable situation and therefore the amount of renewable material within the prototype was set at 50 wt%.

Based on these observations, the prototype requirements were defined as:

7. Cured sufficiently to be dry to the touch at 25°C after 6 hours
8. 0.75 MPa < Peel strength on concrete (brushed and set) < 10 MPa
9. Either
   a. Thermally activated system,
   b. Optically activated system or
   c. Several component system with at least one component liquid at 25°C
10. Materials are non-hazardous (in laying/use/disposal)
11. The sub-floor is visible through a 1cm layer, i.e. within the visible spectrum
12. Made from at least 50 wt% renewable materials with the remainder being non-hazardous materials

The next step was to compare various products in the market place and novel solutions to the prototype requirements. This investigation is shown in the next section.

3.2.3 Results from Initial Screening and Investigation of Candidate Systems

3.2.3.1 Introduction

An initial screen of the marketplace revealed a varied and extensive group of candidate materials. These included concrete, paints, vinyl and screeds. This section describes how some of these candidates fulfil some of the PAF prototype requirements.

Those described below are all industrial systems used in various applications. These systems are compared to the properties that can be obtained during an initial investigation into the principal oleochemical technology and scrutinised in table 1 against the PAF ideal properties.

The principal oleochemical technology was investigated initially for curing time, mechanical properties and glass transition temperature. This was to achieve some indication as to which systems the technology could be similar to in service. For example, if the resin exhibited similar properties to PVC on this small scale, then it can be expected to perform similarly in service as a floor. These other systems were first compared to the prototype requirements.
Concrex is a tough epoxy resin mortar for repairing concrete floors. It bonds strongly to the substrate and does not shrink when cured. It cures to a slip resistant, grey granite-hard finish.

Floor paint is used decoratively in a variety of colours. Although it is hardwearing, it is applied over another flooring, such as concrete. It is primarily used in industrial settings such as factories, showrooms and garages. It is typically dry within 12 hours and is easy to clean when dry (Watco, 2005).

Epoxy gloss paint is generally solvent based and must be applied in well-ventilated areas. It provides a similar function to floor paint with a glossy finish, although the constituents must be handled more carefully since they are hazardous when inhaled (Watco, 2005).

Flow Top is a slip-resistant coating, which can be over-coated. It is suitable for use on uneven and damaged concrete to produce a smooth, high strength surface. It is stronger than concrete and therefore offers a durable finish. Foot and light traffic is possible after only hours of curing time (Watco, 2005).

Vinyl is the second largest volume plastic produced in the world (Vinyl Info, 2005). It is a flexible floor covering provided in roll or tile form that is glued to the sub-floor. It is hard wearing and offers good flammability resistance. Polyvinyl chloride (PVC) is a major constituent of vinyl and the concerns with this material are discussed in section 4.2.2. There are vinyls made from recycled PVC, which reduces overall environmental impact, but does not include renewable material.

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Concrex</th>
<th>Floor Paint</th>
<th>Epoxy Gloss Paint</th>
<th>Flow Top</th>
<th>Vinyl (roll)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cure time</td>
<td>✓</td>
<td>X</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Peel strength</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>✓</td>
</tr>
<tr>
<td>Thermally/optically activated or 2 component</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>X</td>
</tr>
<tr>
<td>Non-hazardous</td>
<td>✓</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>✓</td>
</tr>
<tr>
<td>Translucent</td>
<td>X</td>
<td>X</td>
<td>✓</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>50 wt% renewable raw materials</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
</tbody>
</table>

Table 1. Examination of existing technologies compared to PAF prototype requirements.
These current flooring systems do not fulfil the PAF prototype requirements and all fail the renewable resources criteria. Therefore an alternative has to be sought. The oleochemical binder technology, as suggested by A and F, was investigated and compared to the prototype requirements.

3.2.3.2 Results from A and F Investigation

A and F suggested the initial chemical process to be investigated. There were a number of experimental analyses carried out that showed this system had potential for further investigation and improvement. This system was liquid, transparent, practically odourless and made from a majority of renewable resources.

This technology is based on an ELO (figure 2) and cross-linker (figure 3) that will form a network as the system cures. Although there are potentially hundreds of resin systems, this system was chosen based on the experience of A and F with renewable polymers. The cross-linker was produced at the research institute and again chosen based upon their expertise with this system. The resulting polymer is shown in figure 4.

![Figure 2. Simplified chemical structure of ELO](image)

![Figure 3. Cross-linker formed by heating dipropylene glycol in the presence of maleic anhydride](image)
This chemical process was investigated by using different ratios of cross-linker to ELO. With a molar ratio of ELO: crosslinker of 1:3, theoretically all the epoxide groups of the ELO can react with all the acid groups of the cross-linker. With a molar ratio of 1:1, in theory, all the acid groups of the cross-linker can react with just two epoxide groups of an ELO molecule, resulting in a more flexible polymer. The 1:2 ratio was also chosen, as it would produce a mid-range polymer.

British Standard EN 29117 describes a drying test using plungers, for testing the curing of resins. However, since this equipment was not readily available, a Braive drying time recorder was used as a guide to assess curing time. This has been used extensively in the paint industry to assess drying time of alkyd paints (A and F, 2005).

The mixture was applied on a rectangular shaped glass plate of dimensions 70 mm x 20 mm x 0.5 mm. A needle with a ballpoint was placed on this glass sample carrier and pulled through the mixture at a rate of 12 mm/hour. As the coating cures, the trace left in the coating by the ball identifies each stage of the cure. Initially the coating levels off under gravity. Once it begins to cure, a thin, dry film appears on the surface and so the ball leaves a trace. When the ball no longer leaves a trace the coating is fully cured (Elcometer, 2005).

Dynamic mechanical and thermal analysis (DMTA) involved using a Rheometrics RSA II solids analyser to acquire a value for glass transition temperature (Tg). A Zwick Z010 tensile tester was used to assess mechanical properties such as Young’s modulus, strain at failure and maximum tensile strength (A and F, 2005).

Figure 5 and table 2 show the results below.
Figure 5. Variation of curing time at room temperature, measured using a drying time recorder, in comparison to molar ratios of ELO/Cross-linker (A and F, 2005)

<table>
<thead>
<tr>
<th>Molar Ratio ELO:Cross-linker</th>
<th>Curing Temperature (°C)</th>
<th>Curing Time</th>
<th>Stress-max (N/mm²)</th>
<th>Strain at Fracture (%)</th>
<th>Tg (°C)</th>
<th>Young’s Modulus (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1:3</td>
<td>22</td>
<td>3 days</td>
<td>0.5</td>
<td>40.6</td>
<td>-4.4</td>
<td>2</td>
</tr>
<tr>
<td>1:2</td>
<td>22</td>
<td>3 days</td>
<td>0.4</td>
<td>32.3</td>
<td>-9</td>
<td>0.8</td>
</tr>
<tr>
<td>1:3</td>
<td>150</td>
<td>30 min</td>
<td>1.4</td>
<td>51.7</td>
<td>6.2</td>
<td>3</td>
</tr>
<tr>
<td>1:2</td>
<td>150</td>
<td>30 min</td>
<td>3.5</td>
<td>63.1</td>
<td>14.7</td>
<td>6</td>
</tr>
</tbody>
</table>

Table 2. Variation of mechanical properties tested at room temperature with curing temperature and molar ratio (A and F, 2005)

The main drawback for this system as PAF is its curing time of over 50 hours. As a first step to reducing this, catalysts typically used in the paint industry to aid drying time, were introduced at 1 wt% in order to assess if a reduction in curing time could be achieved. 1 wt% was chosen as it would give some indication of catalyst effect, without saturation affecting the system properties excessively. Manganese is known as a surface dryer for alkyd paints (Hardy, 2004), whereas tin and zinc are used in the form of salts in order to increase electron transfer during reaction. It may be that the manganese dries a thin coating quickly (as is shown by the drying time recorder), but does not work as effectively for thick coatings, which may be laid down as PAF (Hardy 2005). The results are shown in figure 6.
Figure 6. Showing variation of curing time with the introduction of catalysts to the 1:3 ELO:Cross-linker ratio mix

These initial experiments showed that the curing time could be reduced by around 20 hours as a first attempt. Although this is dramatic, this requires further investigation, in order to verify the effect of differing the amount of catalyst. There may also be factors that affect the wider environment that limit their use.

3.2.3.3 Discussion

The mechanical properties were tested three days after the reaction had begun to occur at room temperature as it was thought that the chemical reactions would be complete. It may be that the system continues to age and react, albeit very slowly. Therefore these tests should be repeated several times after reaction begins. It is recommended that they are repeated several days, weeks and months after the two components are mixed, and after aging tests under increased temperature and UV light. This will be expanded upon when the next stage of the project is defined further.

The conclusion that can be reached is that these polymers are rubber-like in their performance, with low Young’s Modulus and high strain at failure. This was advantageous at this stage in the development of PAF as the material can resist impacts and properties may be further modified at a later stage, typically through the use of inclusions and catalysts.

Several prototypes were made to feedback to the innovations group and show what current possibilities were for this substance, given that the drying time is still unacceptable. These are shown below in figures 7, 8 and 9.
Figure 7. Sample of PAF with natural inclusions

Figure 8. PAF with greater amount of coloured inclusions
An important next step for the PAF concept is to consider the effects of different amount of catalysts on the reaction rate. There are also a number of other more powerful catalysts to consider, such as sulphuric acid and sodium hydroxide. These are not considered environmentally friendly and are listed under the hazardous substances regulations (NEA, 2005). They may provide some indication as to how fast the reaction could occur at room temperature and effect on mechanical properties. If it is found that the curing time cannot be improved, even with these powerful catalysts, it is unlikely that the other catalysts will be able to improve it to the prototype properties required and some other system must be found.

This initial investigation has shown that there are a number of possibilities for the PAF concept. However, there are other resins based on renewable systems, cross-linkers and catalysts that may be worthy of investigation for use in PAF. Some of these are described in the further work section that may be considered for use as an alternative concept.

3.2.4 Future Work For PAF

The initial investigation has shown that, based on the materials tested, there is no immediate solution that fits the PAF concept. It has been shown that with this work the prototype requirements cannot be easily reached. The future work for PAF would have to be broken down into a number of further phases. Phase one and two, the initial research and testing exercise, has been completed.

The ELO system has shown promise and a series of well-thought-out experiments will show if this system can fulfil the prototype requirements. The third stage of the investigation would take a further 12 months of project time (A and F, 2005), which would aim to increase the amount of renewable material, reduce curing time using renewable catalysts and develop concepts for application methods.

A SWOT analysis is summarised below.
### Table 3. SWOT analysis of PAF

<table>
<thead>
<tr>
<th><strong>Strengths</strong></th>
<th><strong>Weaknesses</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Potentially sustainable</td>
<td>Knowledge of material in-house requires development</td>
</tr>
<tr>
<td>Based on renewable resources</td>
<td>Costly</td>
</tr>
<tr>
<td>Demonstrates innovative R and D</td>
<td>No immediate gains visible</td>
</tr>
<tr>
<td>True innovation</td>
<td></td>
</tr>
<tr>
<td>Patentable</td>
<td></td>
</tr>
<tr>
<td>Huge customer reach</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>Opportunities</strong></th>
<th><strong>Threats</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Reassert Interface’s position as number one in sustainability with biopolymers</td>
<td>Length of investigation high</td>
</tr>
<tr>
<td>Increases external partnerships</td>
<td></td>
</tr>
<tr>
<td>Leading the way for biopolymers to enter mainstream</td>
<td></td>
</tr>
<tr>
<td>Possible collaboration with US</td>
<td></td>
</tr>
</tbody>
</table>

It can be seen that there is a great deal of work to complete in order to take PAF to stage 2. There are a number of other stages that would follow to get PAF to prototyping stage. It may be that some other work will take the ELO system towards the ultimate aim of PAF, whilst offering some intermediate goals. One of these concepts is shown in the next chapter.

### 3.3 Conclusion

PAF has the potential to be an innovative and sustainable system that offers a unique design system and brings the sustainability message to a wider audience. However, there may not be a solution to the strict requirements of the concept brief within the foreseeable future.

An intermediate prototype was described and it was shown that, with the material investigated, there was no solution yet to these requirements. Therefore a further intermediate goal was required that would bring PAF closer to realisation.
The ELO system was chosen based upon the expertise of leading biopolymer researchers. This system can be transparent, the constituents are fluid at room temperature and the resulting resin exhibits properties that may be of use for a flooring system. This system will not yield an appropriate solution to the PAF concept within a suitable timescale.

There are other options available, using the ELO system, that may be placed within Interface to yield a more rapid result. It is obvious that it is worth using one of these projects as a tool that will allow investigation of the ELO system to continue.

The ‘Sustainable’ Interlock concept is described in the next chapter and is worthy of investigation as an alternative to the use of PVC. This would be a concept that can have wide-reaching implications for the use of renewable materials. It is therefore concluded that the alternative to PAF- the ‘Sustainable’ Interlock system is that which will have priority for future work.
4. Future Work

4.1 Introduction

This chapter discusses the concept of 'Sustainable' Interlock and the criteria for choosing constituents to replace PVC within Interlock. These criteria are discussed and will be developed throughout the project.

Interface’s vision of a sustainable company and community was discussed in Chapter 1. An Interface product, Interlock, will be described in this chapter that is manufactured entirely from PVC. Clearly the use of PVC also does not fit with the corporate sustainability message whilst there are vocal concerns within the environmental community about its use (Greenpeace, 2002, POE, 2005, PANNA, 2005).

The previous chapter discussed the potential for the use of a system based on ELO. This system is considered here as an alternative to PVC within Interlock. This system will be investigated further and potentially modified to create a more sustainable product, whilst offering similar service in practice to the current Interlock product.

This chapter also discusses the experimental work that will be required in order to assess if the replacement material will fulfil the criteria for conditions of use.

4.2 ‘Sustainable’ Interlock

4.2.1 Introduction To Interlock

The specifications for Interlock are that it is a resilient flooring tile that it is manufactured from 100% recycled post-industrial waste. It is available in four top surface finishes and 10 colourways and is available with an anti-static finish. It is a hardwearing, anti-slip, practical and durable flooring that is suitable for light to heavy use such as can be found in an industrial setting.

It is also flexible enough to be used for exhibition stands, retail and hospitality as installation can be fully bonded, tackified or laid loose (Futureproofed, 2005). Once it has completed its useful life, the Interlock can be itself recycled.

An example of an installed section of Interlock tiles is shown below.
This product will continue to play a significant part in Interface’s profile. However, there are manufacturing concerns that need to be addressed if this market is to grow to its potential. These are shown below.

4.2.2 Manufacturing Concerns

A sub-contractor manufactures Interlock for Interface Europe. It is produced using an extrusion process, relying on a heating and cooling cycle for the PVC to form the shape required. This is achieved using a heated extruder and mould.

Although the specifications state that Interlock should be manufactured from post-industrial waste, reducing environmental impacts over the life cycle of the product, there has been a lack of consistency with the quality and quantity of feedstock and virgin material has to be used for a majority of production.

There are a number of concerns regarding the manufacture of PVC that are still being addressed such as the use of plasticisers, chlorine use, dioxin and furan production (Carrol Jr et al, 2000). The chemicals produced as by-products in the production of PVC have been linked to increased likelihood of certain cancers, including testicular (Ohlson, 2000).
Interlock is a single polymer system that would lend itself readily to mechanical recycling into a similar product with a similar requirement for PVC grade. Mechanical recycling uses a number of further processes such as mechanical and thermal methods, requiring energy, which although intensive, will be preferable to incineration or landfill (EC, Green Paper, 2000). The presence of hazardous additives such as lead, cadmium and polychlorinated biphenyls (PCBs) within large-scale PVC waste streams results in recycling issues, as these contaminants must be diluted with virgin material.

Chemical recycling of PVC is environmentally less preferable and less attractive in economic terms. There are therefore a limited number of initiatives that have resulted in the construction of industrial plants, or may lead to the creation of such plants in the near future (EC, Green Paper, 2000).

In the year 2000 within the European Community (EC) around 100,000 tonnes of PVC were recycled compared to 2.9 million tonnes that was sent to landfill.

Incineration is a method of disposal that is worthy of note in this instance, with careful consideration for emissions. Approximately 600,000 tonnes of PVC are incinerated per year in the EC. PVC represents about 10 wt% of the plastic fraction incinerated, although it contributes between 38 and 66% of the chlorine content in waste streams being incinerated (EC, Green Paper, 2000).

On incineration, PVC waste generates hydrochloric acid (HCl) in the flue gas that requires deactivation with a neutraliser such as lime. It is estimated that the incineration of PVC results in, on average, 1-1.4 kg of residues with this lime process per kg of PVC incinerated.

PVC is also currently the largest contributor of chlorine into incinerators, which contribute around 40% of the dioxins into the EC. Dioxins have been linked to a number of health concerns. It has been suggested that reducing the chlorine content in incinerators will reduce the production of dioxins by a second or third order relationship (EC, Green Paper, 2000).

There have been attempts to make PVC biodegradable through the addition of ketones (Kaczmarek, 2003). Although these studies are promising, they result in a decrease in photochemical stability. It is not yet known how the products of photochemical degradation will affect the environment.

It is obvious that PVC has a number of environmental concerns associated with its manufacture. It would therefore be preferable to offer the same qualities that Interlock currently offers with some material alternative.
4.2.3 Concept Description

Since PVC has a number of environmental concerns associated with its manufacture and disposal, producing Interlock with a different material could potentially offer great environmental benefits.

The ELO-based technology has been investigated as part of the PAF project and can provide a foundation for a renewable alternative to Interlock. This technology has exhibited the potential for modification and its properties are currently similar to rubber. There is the possibility of using this material as part of a composite system to increase wear resistance in service.

The PAF investigation has been focused on reducing curing time of the system at room temperature, although this can be reduced to 30 minutes at 150 °C. Since Interlock is currently extruded at elevated temperature and pressure, there may be reductions in energy requirements during manufacture.

This resin would replace PVC by offering a similar service in use at reduced environmental cost. 'Sustainable' Interlock is therefore described in the same manner as Interlock- hardwearing, anti-slip, practical and durable flooring. It is suitable for light to heavy use, such as can be found in an industrial setting. It is also flexible enough to be used for exhibition stands, retail and hospitality as installation can be installed with an adhesive or laid loose.

Interlock tiles lock together for ease of laying and can be lifted and re-laid. No adhesive is needed, this reducing the localised environmental impacts associated with adhesive use, such as airborne contaminants.

The floor can be scrubbed or mopped with ordinary household detergents. It can be swept and vacuumed without obvious disturbance to the tiles.

The visual impact of the tiles can be altered through the addition of dyes also from renewable resources. They can also be laid randomly to reduce waste in installation.

A SWOT analysis of 'Sustainable' Interlock is summarised below.
<table>
<thead>
<tr>
<th>Strengths</th>
<th>Weaknesses</th>
</tr>
</thead>
<tbody>
<tr>
<td>More sustainable that PVC</td>
<td>Knowledge of material in-house requires development</td>
</tr>
<tr>
<td>Can use established manufacturing techniques</td>
<td></td>
</tr>
<tr>
<td>Demonstrates innovative R and D</td>
<td></td>
</tr>
<tr>
<td>Patentable</td>
<td></td>
</tr>
<tr>
<td>Similar investigations in the US</td>
<td></td>
</tr>
<tr>
<td>Can be continued within the UK</td>
<td></td>
</tr>
<tr>
<td>Relatively high customer reach</td>
<td></td>
</tr>
<tr>
<td>Reduction of transport costs as low density product sought</td>
<td></td>
</tr>
<tr>
<td><strong>Opportunities</strong></td>
<td><strong>Threats</strong></td>
</tr>
<tr>
<td>Reassert Interface’s position as number one in sustainability with biopolymers</td>
<td>Length of investigation relatively high</td>
</tr>
<tr>
<td>Raise Interface’s profile in Green Chemistry Network</td>
<td></td>
</tr>
<tr>
<td>Novel designs can be produced quickly</td>
<td></td>
</tr>
</tbody>
</table>

Table 1. SWOT analysis of replacing PVC in Interlock with renewable chemicals

4.2.4 Target Audience and Customer Benefits

The market for Interlock is growing within the residential sector and sales are currently around 60,000 m² per annum. There are a number of strategic places that Interlock can be positioned to offer benefits to both user and purchaser. For example, the concept can be marketed to the hospitality and leisure sector by extolling the benefits that arise from easy cleaning with regular detergents. An advantage for the exhibition sector is that the product is easy to install, remove and re-install in the same manner as Interlock, but is better for the environment overall.
Primarily this concept is hardwearing, practical flooring. However, the add-on benefit is that it is designed to be environmentally preferable to the original Interlock. This will be expanded in the next section. There will be sectors, such as certain residential areas, where the environmental credentials will be of primary importance and therefore will require greater promotion.

When marketing this product to the residential sector, there will be a greater number of persons per metre squared of flooring sold receiving Interface’s message, therefore promoting greater awareness across the board of sustainability. The concept will be extremely influential in raising customer awareness of Interface and the 2020 vision.

The concept must be fit-for-purpose, i.e. it must perform the function required of it. The material that makes up the ‘Sustainable’ Interlock is crucial and the manner in which material is chosen will be discussed in the next section.

4.3 Selection Criteria

4.3.1 Background

The constituents that form ‘Sustainable’ Interlock must be chosen carefully. There are a number of factors that must be considered before a material can be used such as health and safety in manufacture, its fitness-for-purpose, health and safety in use, environmental impacts throughout lifecycle and its general processability.

For example, it may be that a material can be made biodegradable through the inclusion of chemicals with overt health risks during manufacture: would this trade-off be appropriate? This section will describe how these concerns will be addressed throughout the progression of this project.

When considering if a material is fit-for-purpose, it can clearly be observed that the requirements for a floor include, but are not limited to- reduced environmental and economic impact per unit of flooring that provides the function required of it.

This leads to the question: what is the purpose of flooring? There are a number of ways that a flooring unit can be assessed depending on its use. Consumers make strong distinctions between categories of floor (O’Neill, 2003). Consumers see wood and ceramic as permanent flooring and vinyl, laminate and carpet as temporary floor coverings. They also see the buying process as either practical, e.g. laminate and vinyl, or emotional, e.g. hardwood and ceramic. It is clear that ‘Sustainable’ Interlock will be a purchase to perform a practical task for most sectors and therefore this should be the primary consideration for the function that will be selected for a flooring unit.
These functions would include providing stable dimensions, impact resistance, wear resistance, thermal insulation and electrical insulation. There are British Standards that describe the way in which resilient flooring may be tested and these can give some idea of the functions of a floor in use. Some of these tests will be described in section 4.4.2.

The secondary purposes of this type of flooring unit are to provide aesthetic qualities, texture and reduce environmental deficits (although it could be argued that this is a primary purpose for 'Sustainable' Interlock, this is already considered in the selection of ELO). The selection criteria for the material must be defined in order to reach conclusions about the suitability of particular constituents before further investigation. These are described here.

4.3.2 Development of Selection Criteria

There are two stages to the selection of material. There must first be a screening and ranking process to give a shortlist. Secondly detailed supporting information is sought about the shortlisted candidates, allowing a final choice to be defined (Ashby, 1999). The use of the system as a flooring unit has been defined, although not its dimensions or mass.

This first section must be divided into screening- deciding those that provide the essential attributes and then ranking through supporting information.

The requirements on the material can be divided into three categories: non-negotiable, those that should be optimised and those that are negotiable, but preferable. If a system fails those criteria that are non-negotiable, then it should be discounted. Those that pass this initial screening will be ranked using the optimisation criteria and then chosen based on their preferable criteria. This is further discussed in section 4.3.7.

The British Standards tests that simulate conditions in service require around one metre squared of material to carry out a number of tests. During the screening and ranking phase, there are a number of variants that should be considered before selecting the leading candidates- for example, cross-linker: ELO ratio, heating cycles, colourfastness and the use of filler. Therefore, in order to reduce the amount of material required for the experimental phase of selection, there should be an initial screening process that uses a smaller volume of material, based upon the expected conditions in service, described in section 4.3.6.
Originally the system of ELO and cross-linker was defined as it forms the basis for 'Sustainable' Interlock. This system is designed to provide reduced environmental impacts in comparison to PVC. There are a number of candidates that can offer this, but they must be suitable and practical for this application. The main constituents are discussed first.

4.3.3 Environmental Aspects

In section 4.2.2 the perceived environmental problems with PVC were discussed. It was concluded that replacing PVC with another material would be preferable for the environment.

In order to assess environmental performance a complete life cycle analysis should be performed from cradle to grave. However, at this early development stage, this would prove rather demanding. Therefore with this difficulty in mind, the possible environmental detriments of any system should be considered and weighed against the gains to the environment of not using PVC. This will not be quantified at the ranking stage, but will be considered during the course of this project.

There have been some studies into the environmental benefits of using an ELO-based substance in place of a petrochemical alternative in a coating (Diehlman, 2000). This particular study concluded that replacing a petrochemical constituent with ELO was ecologically preferable. This was true in a number of categories such as energy consumption, carbon dioxide emissions, nitrogen oxide emissions and the use of primary energy sources. The study suggests that the use of renewable sources becomes more environmentally preferable, the more synthesis steps required to manufacture the petrochemical constituent.

Linoleum is also based on linseed oil, but results from the direct oxidation of the oil. The flax is separated into the oil and linen. The oil is then placed in thin layers onto a fabric backing and exposed to the air to create a rubbery surface. It is then seasoned and left over a period of several weeks to ensure full cure (Encyclopaedia, 2005).

Epoxidised linseed oil is one part of the system that may be substituted. There are other systems that have been studied such as soybean oil, rapeseed oil, palm oil, canola oil and olive oil (Khot et al, 2000). The differing chemical structures of the oils tend to lead to differing mechanical properties. Linseed oil has a long-chained structure and was chosen based upon the expertise of A and F. Although other oils have not been completely discarded at this stage, they will be of secondary concern during this investigation.
However, studies also indicate that the most unsaturated oils, such as soybean and linseed oil, are appropriate for creating a high cross-linking density and therefore a high stiffness (Boquillon, 2000). This high stiffness will be essential if the system is to be poured onto a floor and will be discussed further in section 4.3.

Linseed is abundant around the world; in 2003, 634,538 tonnes of linseed oil were produced globally from 2.5 million hectares of land devoted to linseed production (Jenica, 2005). ELO is also presently available commercially and used in applications in coatings and plasticisers (Miyagawa et al, 2004). Therefore this oil is ideal for a commercial high-volume floor product.

There have been described a number of cross-linkers that can work with ELO to create a polymer within a much shorter timescale than the days required for linoleum production (Boquillon, 2000). The product that results also has a much higher stiffness than the linoleum. Some of the cross-linkers that have been used are described in table 2.
<table>
<thead>
<tr>
<th>Name</th>
<th>Formula</th>
<th>Molecular weight (g/mol)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phthalic anhydride (PA)</td>
<td><img src="image" alt="Phthalic anhydride" /></td>
<td>148</td>
</tr>
<tr>
<td>Cis-1,2,3,6-Tetrahydrophthalic anhydride (THPA)</td>
<td><img src="image" alt="Cis-1,2,3,6-Tetrahydrophthalic anhydride" /></td>
<td>152</td>
</tr>
<tr>
<td>Methyl-tetrahydrophthalic anhydride (MTHPA)</td>
<td><img src="image" alt="Methyl-tetrahydrophthalic anhydride" /></td>
<td>166</td>
</tr>
<tr>
<td>Methyl-hexahydrophthalic anhydride (MHHPA)</td>
<td><img src="image" alt="Methyl-hexahydrophthalic anhydride" /></td>
<td>168</td>
</tr>
<tr>
<td>Methyl-endomethyleneterahydrophthalic anhydride (METH)</td>
<td><img src="image" alt="Methyl-endomethyleneterahydrophthalic anhydride" /></td>
<td>178</td>
</tr>
</tbody>
</table>

**Table 2. Cross-linkers that may be used to form a polymer with ELO (Boquillon, 2000)**

In this study, the THPA, METH, MHHPA and MTHPA were heated with the ELO at 110 °C for 15 minutes before a catalyst was added. PA was heated at 145 °C for 15 minutes before the addition of a catalyst. The temperatures were chosen to be just above the melting point of these cross-linkers.

The purpose of the catalysts was to increase the curing that took place at 150 °C for 15 hours, followed by 170 °C for 1 hour. This cycle is chosen as it allows stable properties to be obtained, without evidence of thermal degradation (Boquillon, 2000). The catalysts used are organic bases that are typically used in organic synthesis (Hardy, 2005).
Although this study describes a number of useful synthesis steps, cross-linkers and solvents must be chosen and investigated carefully, in order to utilise the most efficient and environmentally preferable system.

The cross-linker will form a principal part of the supply chain, since it will form the raw material input in conjunction with the ELO. Considering this, then it should not nullify the benefit of using ELO in preference to PVC with environmental hazards during manufacture.

There have been a number of cases described in the literature that shed concern on the use of these cross-linkers, which often use maleic anhydride for synthesis. For example, acute inhalation of maleic anhydride used in the production of many of these cross-linkers, results in irritation of the respiratory tract and eyes in humans (EPA, 2000). Chronic exposure has been linked to chronic bronchitis, asthma-like attacks, and upper respiratory tract and eye irritation. Kidney effects were observed in rats chronically exposed to maleic anhydride by placing the chemical in the stomach (EPA, 2000).

The acute effects in humans from exposure to phthalic anhydride consist of irritation to the eyes, respiratory tract, and skin, but with no permanent effects. Chronic effects include conjunctivitis, rhinitis, rhinoconjunctivitis, bronchitis, and irritation of the skin and mucous membranes of the respiratory tract. Animal studies indicate that chronic exposure to phthalic anhydride vapour causes congestion, irritation, and injury to lung cells (EPA, 2000).

It can therefore be concluded that the choice of constituents for ‘Sustainable’ Interlock must be carefully considered in order to create a more environmentally preferable product.

One of the benefits defined of ‘Sustainable’ Interlock is that it is environmentally superior to PVC. This is not something that can be quantified easily. Since conducting a life cycle analysis of every component to be used within ‘Sustainable’ Interlock is not practical during the first selection stage. Therefore a ranking system should be used for these components during the second stage of selection.

It has already been indicated that ELO has reduced environmental impacts in comparison to a petrochemical counterpart. In order to ensure that the materials can be ranked against each other and also prove environmentally preferable to PVC, strict criteria must be laid down to define the mass of renewable material that will be used within ‘Sustainable’ Interlock. The way in which this is defined is described in section 4.3.7.
4.3.4 Health and Safety Requirements

The primary consideration for the use of any material is that it fulfils all health and safety requirements. The law sets down these requirements and those that do not fulfil these requirements must be discarded immediately. Therefore health and safety requirements are a non-negotiable requirement.

There are two types of health and safety requirements: those required during the manufacturing phase, including the materials and the health and safety of the ‘Sustainable’ Interlock in use and disposal.

The health and safety during manufacture will include production of material test samples, prototypes, trials and large-scale production. Each constituent can be procured with an appropriate data sheet comprising chemical data and health and safety requirements. These requirements should be followed at every stage, if they cannot be followed, then the material must be discarded. If safety procedures are put in place such that the constituent may be used again, then it may be reconsidered. The safety procedures for the components used will be included in the 30-Month Report.

The health and safety during manufacture will also include the use of machinery and safe practices. These will be assessed at the time of prototype manufacture, although currently there are no restrictions that preclude the development of this system, since the manufacturing apparatus is not yet in place.

The health and safety of Interlock in use is included in the British Standards, described in section 4.4.2. The disposal considerations are given below.

4.3.5 Disposal Considerations

Disposal considerations are of low importance if the material is made from renewable materials, so long as the material remains inert during degradation. There will be a number of disposal routes available for each material which will have differing impacts over the lifecycle of ‘Sustainable’ Interlock. It would be desirable to have a biodegradable polymer, but it is not essential. Therefore disposal will be considered during the secondary ranking phase.
4.3.6 Material Properties

The function of this type of flooring will depend on its use. If a chair resting on the floor is considered, then the function of the flooring will be to resist this static load. A material is required that will perform this function, whilst retaining shape after the load is withdrawn, which ensures materials can be assessed on this performance.

One option would be to assess all materials using all the flooring tests that are in place with the British Standards. Since this is not practical, due to the high number of choices at this stage and the large volume of material therefore required, an intermediate ranking system is required that can be derived from examining the conditions that occur in service and relating these to the properties required. There will be some commonality with the material properties requiring assessment and therefore the number of tests can be reduced dramatically.

Initially there are a number of factors during manufacture to consider that can alter the properties of this material. These include cross-linker amount, time at elevated temperature and the inclusion of fillers or fibres for strengthening as composites. If the properties that are required from the material can be maximised before manufacture of prototypes, then the total volume of material required can be reduced. There can also be confidence in the material in testing at prototype stage.

The material properties of PVC, such as Young’s Modulus, elongation to failure etc can be examined and the material simply altered to try to emulate these properties. However, the current Interlock product appears to be grossly over-specified in terms of its thickness and performance in use. This will be investigated in the next 6 months work and the results included in the 30-Month Report.

The size and shape of the Interlock tiles is fixed by existing production moulds. As the dimensions of the material are fixed and lower mass is preferable, the thickness may be reduced in order to reduce transport costs, financial burden and increase ease of fitting.

The dimensions of the material are shown simplified in figure 2. The tile is square and of width, w, thickness, t, mass, m, density, ρ.

The mass of the tile is given by:

\[ m = \rho tw^2 \]

The width of material is fixed, although ρ and t can be varied. The tile must be sufficient to carry the load, F, without failure.
The tile is placed freely on a rough surface and not bound to the floor; therefore the material is constrained at the edges only by other Interlock tiles. These tiles are in turn held in place by the edge of the room. This model is not ideal but designed to give some idea of how the tests can be simulated. Scenarios for other tests will be fully described in the 30-Month Report.

![Figure 2. Example of plate being tested under static load](image)

For a plate:

Second moment, \( I = (\frac{wt^3}{12}) \)

There will be the onset of buckling at:

\[
F = C \left( \frac{I}{Y_m} \right) \times \left( \frac{\sigma_f}{w} \right) \quad \text{where } Y_m \text{ is the distance from the neutral axes of bending to the outside of the beam, i.e. } t/2, \\
C \text{ is a constant, in this case, } 4 \text{ and } \sigma_f \text{ is the fracture strength.}
\]

Therefore:

\[
F = \frac{4 \times wt^3 \times 2 \times \sigma_f}{12 \times t \times w} = \frac{8t^2\sigma_f}{12}
\]

Rearranging for \( t \), since it is variable:

\[
t^2 = \frac{(6F)}{(4\sigma_f)}
\]

Inserting this into the equation for mass of plate, which requires minimising:

\[
m = \rho \left( \frac{6F}{(4\sigma_f)} \right)^{1/2} \left( \frac{(4\sigma_f)^{1/2} w^2}{203} \right)
\]
Since \( w, F \) and \( l \) are all fixed, the mass that must be minimised is proportional to those remaining constraints. Therefore the material index, \( M \), that must be maximised is:

\[
M = \frac{\sigma_f}{\rho}
\]

This can be continued for other flooring tests and achieve similar material indices. This will form the basis of the material selection methodology shown in the next section.

The table below shows typical material indices that require maximisation for the case of the plate shown in figure 2, where, \( E = \) Young’s modulus, \( \rho = \) density, \( \sigma_f = \) fracture stress, \( \lambda = \) thermal conductivity, \( \alpha = \) linear expansion coefficient and \( C = \) cost per unit weight of material.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Material Index, ( M )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum weight of stiff plate</td>
<td>( \frac{E}{\rho} )</td>
</tr>
<tr>
<td>Minimum weight of strong plate</td>
<td>( \frac{\sigma_f}{\rho} )</td>
</tr>
<tr>
<td>Minimisation of thermal distortion</td>
<td>( \frac{\lambda}{\alpha} )</td>
</tr>
<tr>
<td>Minimum cost design of a stiff plate</td>
<td>( \frac{E}{C\rho} )</td>
</tr>
<tr>
<td>Minimum cost design of a strong plate</td>
<td>( \frac{\sigma_f}{C\rho} )</td>
</tr>
</tbody>
</table>

*Table 3. Typical predicted material indices if Interlock is simulated as a plate in flexure*

These calculations can guide the initial selection of material that is described in the next section.

### 4.3.7 Methodology

The criteria are divided into three categories:

- **Red:** Non-negotiable- if a material fails any of these criteria then it should be discarded.
- **Amber:** Require optimisation- systems can be ranked on these criteria and they should be maximised.
- **Green:** Negotiable, but preferable- these are criteria that it is preferred the system provide, but it will not preclude further development if they are absent.
The criteria described are not defined in absolute terms. For example, the product may well be expected to cost more than the current PVC product. However, there is a limit to the premium that consumers will pay, or Interface will absorb. Therefore although cost should aimed to be minimised, there will be a level at which the product is economically unsustainable. This level is as yet unknown, but will feature in later calculations, at month 42 of this project, when the impacts of large-scale production are identified.

It is also recognised that the criteria described must be well defined. The other criteria listed here will also be investigated in order to calculate a threshold level, below which a system is unacceptable. These investigations will be documented as the project progresses.

The materials will also be tested according to the flooring tests, at a later stage. This final process will result in a final ranking that will determine the materials to take to trial stage.

There will be more criteria that are added as the project develops, but the initial criteria are defined in table 4 below.
## Table 4. Selection criteria for materials to be used in ‘Sustainable’ Interlock

These selection criteria can be used to guide material testing and then flooring testing. The diagram below shows how these criteria will be fed into the assessment pipeline. The candidate system has already been chosen, which will be based on ELO (section 4.3.3).
Selection of a Candidate System

Non-negotiable

Materials Testing

Rank Materials

Materials rejected

Flooring Tests

Materials rejected

Negotiable but preferable

Selected Material

Figure 3. Process for selection of material with inputs at stage and gate process

The time taken for each of these stages can be estimated and is shown in the Gantt chart (section 4.5).

The materials that pass the initial screening will be used in material testing, described in section 4.4.1. There are a number of variables that may be considered at this primary stage and these must be selected carefully in order to maintain a sensible testing regime.

The primary investigation will be to change the cross-linker: ELO ratio and assess how material properties can change through a range of ratios. Once several key samples have been identified, they will be put through temperature cycles from 30-180 °C against time and the changes assessed again. This will aid the identification of key samples that can then be used for colourfastness tests, for example.

Initially it is prudent to examine a wide-range of materials in order to obtain a good knowledge of the range of properties that may be expected. This must be fed back into the selection process, so that the process begins to look more like figure 4 (shown below).
Figure 4. Process for selection of material with feedback loops

The materials tests that take place after initial screening will be based on the material indices derived from examination of the requirements in service, based on the example shown in section 4.3.6. It is anticipated that these material tests will enable ranking that will result in rejection of a number of materials after each cycle.

4.4 Experimental Work

4.4.1 Material Tests

The material tests are important to establish the material properties that give rise to the material indices and ultimately lead to performance in service. The material indices will be used as a guide to the performance that would be expected and the data used to eliminate material at an early stage of the process.

There are a number of ways in which to determine material properties. As an example, the most common for determining $E$, $\sigma$ (for failure and yielding) is a tensile test using a tensile tester such as a Testometric Micro 350. This involves taking a sample of known dimensions and applying a force, or continuous movement until the sample fails. The resulting graph of force versus distance moved can be converted into a nominal stress-strain graph since:
Stress, $\sigma = F/A$ where $F$ is the force applied and $A$ is the nominal cross-sectional area.

And strain, $\varepsilon = \delta l/l$ where $l$ is the distance moved.

From the graph $\sigma_y$ (yield stress) and $\sigma_f$ can then be determined.

![Schematic stress-strain curve](image)

Figure 5. Schematic stress-strain curve

This is just one example of tests that are available to determine material properties. Those that are used for subsequent testing will be described fully within the 30-Month Report.

These tests are designed to give an indication of material properties and hence aid the ranking system and add information to facilitate rejection. Once there are a number of lead candidates identified in this screening phase, they will be subject to the negotiable requirements and subsequent testing commonly used for resilient flooring.

It is expected that with each variable, such as time at temperature for cure, inclusion of filler and colour fastness assessed, the results of these material tests will be documented in the 42-Month Report.

4.4.2 Flooring Tests

The lead candidates from the material tests will be manufactured using Interlock moulds. These will then be tested using the typical flooring tests. It is expected that this will take place at 38 to 42 months on the project schedule.
Flooring tests are designed to replicate that which occurs in service. These tests focus on abrasion resistance, dynamic loading, static loading, flammability and appearance retention.

There are a number British Standards that govern the testing of resilient flooring in the same manner as carpets are tested. These British Standards will be used in the second phase to test if 'Sustainable' Interlock is fit-for-purpose. Those that are of primary importance are dry slip resistance (BS EN 13893), wet slip resistance (DIN 51130), fire rating (BS EN 13501-1), colour stability (BS EN 20105), dimensional stability (BS EN 434), residual indentation (BS EN 433), chemical resistance (BS EN 20105 B02), abrasion resistance (BS EN 660.1) and specification (BS EN 650:1997).

These tests will establish those materials that will be able to withstand conditions in service and therefore establish lead candidates for 'Sustainable' Interlock. These lead candidates will then be manufactured in trial production.

4.5 Gantt Chart

It is predicted that this project will be completed within the time scale shown on the Gantt chart (figure 6).

The ELO has been obtained and the cross-linker is currently being manufactured on a lab-scale. The next step is to obtain moulds to cure the system in, for the material tests.

The variables in manufacture to be considered at this stage are the ratio of cross-linker: ELO, the time for curing, the temperature for curing, type of dye and renewable fillers to be used. These will all affect the 'amber criteria' described in section 4.3.7. In each case, lead candidates will be taken from each test result and put forward for further evaluation and modification.

Selecting renewable fillers will also require an evaluation of Interface's waste stream to assess if there are other materials that may be used by this system. This will take place mid-2006.

Once the material tests (including tests for chemical resistance and thermal stability) have been completed, lead candidates will be identified and assessed using conventional flooring assessment.

This will ultimately yield a flooring system that fits with the defined criteria. There will be a prototype of a novel, resilient flooring product based on renewable material and manufactured in an environmentally preferable way.
Figure 6. Gantt Chart showing progress to month 48
4.6 Summary

This report has shown that successful steps are being made towards sustainability using traditional methods of resource reduction, waste reduction, renewable energy use and redesign.

The attempts to introduce renewable and recycled feedstock have been described, which are further steps towards sustainability. However, it has also been shown that radical redesign of the product and process is required in order to truly achieve a sustainable company.

One of these projects has been described as PAF, which, although promising, is not a long-term solution. Therefore, an intermediate product is preferred.

'Sustainable' Interlock fits with Interface’s core competencies and will replace an environmentally inferior product.

The outcome of this project will be a novel, resilient flooring product based on renewable material and manufactured in an environmentally preferable way.
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MATERIAL REDACTED AT REQUEST OF UNIVERSITY
Dianne Carter

30-Month Report

01.10.05 - 01.04.06

“Towards Sustainable Design and Manufacture of Textile Flooring Products”
Abstract

The EngD project is looking at more sustainable flooring solutions in the context of Interface's goal to be a sustainable company by 2020.

Success has been in introducing renewable content into the current textile-flooring product. In a previous report (Carter, 2004) the introduction of recycled filler into the tile backing has shown that the Graphlex backing system can incorporate recycled material up to 67 wt%.

An innovation project Pour-A-Flor (PAF) was described and an initial investigation was conducted into the possibility of using a bio-resin within this concept. The preliminary investigation focused on measuring and then reducing the curing time of the resin.

The 2-year Dissertation described the potential for this resin to replace poly-vinyl chloride (PVC) within Interlock- a resilient tile system. PVC is unsustainable and a replacement of lesser environmental impact is required urgently. There is a drive towards focusing on the function that the material provides and providing this same function with a different product. In addition to PAF the bio-resin may be used in other applications. The possibility of using it as a backing system is also considered in this report.

This report describes the process of manufacturing the Glasbac tile backing system (this shows that the application process on-site is relatively straightforward). The current system incorporates PVC, plastisol and filler, all of which are to be considered for substitution as they are sourced from virgin non-renewable materials. The work described here examines the first of these, i.e. replacing the PVC with the bio-resin.

As part of the investigation, the process of linoleum manufacture is also considered. Since this product derives from linseed oil and is manufactured in sheet form, it is worthy of comparison.

The experimental methods used in assessing the material properties of the bio-resin are described in this report. These are used as part of the preliminary investigation only and are not yet indicative of performance in service (there are variations in characteristics observed due to manufacturing differences).

The further work section describes in detail the work to be undertaken in the next twelve months, including the flooring tests. There is also a Gantt chart showing up to the 60-month reporting period.
Glossary

ELO: Epoxidised linseed oil

Bio-resin: A resin that is based on renewable resources

PVC: Poly-vinyl chloride- a versatile thermoplastic used in a number of applications

Top-cloth: Yarn typically tufted through a cloth, however, it can be produced through fusion bonding or other methods. This is the surface of a carpet that will be exposed.

Pre-coat: A coating typically made from latex that is used to secure the tufts in the top-cloth. It is applied before the backing system.

Cross-linker: A chemical that has the ability to provide cross-linking of another through the use of atomic bonding.

Glasbac: A patented backing system manufactured by Interface, made from thermoplastic resins and fibreglass.

Graphlex: A patented backing system manufactured by Interface, made from bitumen, polymers and fibreglass.
1 Introduction

1.1 Summary of Work Described in the 24-Month Report

The 24-Month report summarised the work achieved thus far with this EngD project. The background to the carpet-making industry was described as a prelude to understanding the manufacturing processes and the steps that have been taken towards sustainability at Interface.

The global progress of Interface Inc. in moving towards their vision of sustainability was described. This showed that although progress has been made within company restraints, significant innovation is required in order to become a sustainable company.

One area, towards which this project has made a contribution, is the introduction of recycled filler into the backing system, ultimately increasing recycled content by weight to over 70%. In order to achieve this successfully, some degree of refinement of the manufacturing cycle was required and developed. Details are given in the 12-month report.

Innovation concepts are being examined by Interface in order to alter the focus of the company away from carpet tile and towards flooring solutions. This builds upon the introduction of the Evergreen Lease concept (see 6-month report for details). One such innovation is the concept of Pour-A-Flor (PAF) that has been described in detail in the 24-Month report.

The PAF concept introduced a bio-resin to Interface. This bio-resin is based on epoxidised linseed oil (ELO), a resource manufactured from agricultural crops and therefore renewable and potentially sustainable. The bio-resin could potentially be used in a number of applications such as a backing system, lamination of samples, replacement material, however, its properties (Young’s Modulus, stress at failure and strain at failure), material processing and chemistry need to be understood. Chapter 5 of this report describes the process of assessing these properties.

1.2 Project Direction in the Current Reporting Period

The bio-resin was first described in the 18-month report. A major component of the resin is epoxidised linseed oil. It is cross-linked with a di-acid in order to cure. Although this can occur at room temperature, the time to cure is greatly reduced by elevated temperature (Carter, 2005).
Linseed oil is also used in such applications as lacquers and the manufacture of linoleum. This report describes the manufacturing process for linoleum and compares the curing process of the two products, the bio-resin and linoleum. There are other factors that may be considered such as material properties, use in service, costs etc. However, this report focuses on the curing process as it shows that the bio-resin technology is novel and distinct. The curing time exhibited for linoleum is simply not feasible for a concept such as PAF.

The manufacture of a PVC-backed carpet tile is also described in order to understand how the two processes differ, especially within manufacturing time constraints. This manufacturing process is also described in order to evaluate if the bio-resin may be used within the current process ideally with few modifications.

The experimental techniques used to assess the Young’s Modulus, nominal strain to failure and nominal peak stress of the bio-resin are also described in Chapter 5. The project plan for future experiments is also shown in detail for the next six months in Chapter 6 as well as a plan through to the end of this project.
2 Linoleum

2.1 Introduction

As previously mentioned, linoleum is a flooring product that is manufactured from linseed oil and other constituents. The bio-resin that is the focus of this project is also based on linseed oil—although it is epoxidised. A full description of the curing process can be found in the 24-Month report.

It is important that the history and manufacturing process of linoleum is understood as it may offer insights into the manufacture of the bio-resin.

Linoleum has been manufactured for nearly 150 years (Simpson, 1997) and over this time production processes have been optimised. The basic process, however, remains the same. This chapter describes the way in which linoleum was developed as a product and how the manufacturing process has been refined during the last century and a half.

2.2 History

In 1860 Frederick Walton, a rubber manufacturer in England, during his daily work noticed that linseed oil formed a leathery skin on top of paint. He realised that he could put this characteristic of the oil to good use as a rubber substitute when reduced, mixed with filler and pigments and dried on a canvas backing. That year he patented what he termed 'linoxyn', derived from the name of the main constituent and the method of manufacture (Simpson, 1997).

He later improved this invention and in 1863 applied for an extended patent on what he called 'linoleum', manufactured from the mixing of linseed oil, powdered wood or cork, resins, pigments, ground limestone and drying agents. Frederick derived the term linoleum from the Latin words for the flax plant and oil: linum and oleum respectively (Sarin, 2004).

It soon became a popular term by virtue of the various imitators producing similar products and Frederick did not have exclusive rights for its use. He had not patented the name and had instead described this new invention as an 'improvement to the manufacture of Wax cloth for floors'. Therefore in 1877 as soon as the patent ran out, the name linoleum was deemed generic, thus enabling floorcloth manufacturers to begin producing their own versions.
The floorcloth or oil-cloth industry was widespread in Scotland and Lancashire during the mid nineteenth century. It had begun in the early eighteenth century as a large-scale industry and the process had changed little since. Canvas was tightly stretched across wooden frames in large rooms and workers would use wooden platforms to support themselves as they applied the constituents with trowels and large brushes. They would paint the cloth with size, a thin liquid designed to seal the canvas, much like a primer, followed by the addition of treacly paint. Pumice stones were used to create the smooth finish desired. The floorcloths would then be moved to a printing room for the application of patterns before a final varnish to seal the design (Manson, 2003).

The advantage of the new linoleum was that it was thicker, more resilient and waterproof. The industry began to expand rapidly as the demand for such a floor covering increased and floorcloth manufacturers began to imitate the manufacturing techniques and constituents. It had taken less than three years between the patenting of linoleum and the report of steady sales from the Linoleum Manufacturing Company and three years later it was exporting to the United States and Canada.

The next improvement in linoleum manufacture came after Frederick Walton had moved the technology to the United States in 1872, helping to set up the American Linoleum Company. In 1882 he was granted the first in a series of patents describing inlaid linoleum, which ensured that patterns ran all the way through the surface of the linoleum (Simpson, 1997).

When the inlaid linoleum was first manufactured, it was in the same form as mosaic tiles, where the patterns would be cut out of pieces of linoleum, fitted together to form a pattern and then through the application of heat and pressure the design was set on the canvas backing. By 1892 he had managed to combine these processes so that they could be undertaken by one machine.

Between 1874 and 1913 the volume of linoleum exported from the UK increased tenfold, despite the overall reduction in exports of 29 % (Sarin, 2004). The production of linoleum continued to diversify with more economical products becoming available and the use of material from international sources- linseed oil from America, cork from Portugal and Spain, jute from India and Pakistan and limestone from the UK.

For nearly a century between the 1870s and 1960s linoleum was the most widespread manufactured floor covering in existence (Sarin, 2004), until it was usurped by the vinyl industry. The process of manufacturing true linoleum is time-consuming and has changed little in process since Frederick Walton's last patent application.
Therefore we can conclude that although the industry is fully mature, the drying time achieved is unacceptable for use in PAF.

### 2.3 Manufacturing Process

Linseed oil is derived from the flax plant. It is an annually self-pollinating plant that takes around 100 days to mature to between 40 and 91 cm in size (Flax council, 2005). The raw oil is extracted from the seeds via hydraulic pressure and is pale in colour (Encyclopedia.com, 2005).

Linseed oil was oxidised originally through the process of boiling in a lead vat to form a thick substance called linoleum cement (Flax council 2005). However, oxidised linseed oil is now produced from the addition of chemical accelerators to heated raw linseed oil to decrease drying time.

Oxidation is the process of a molecule losing electrons or the gain of oxygen. In linseed oil this results in a relatively stable compound with a lower latent energy. Epoxidisation, like that used for the bio-resin forms a cyclic ether with only three ring atoms at an angle of 60 °, which are highly strained (figure 1). The epoxide is therefore highly reactive in comparison to the oxide.

\[
\begin{align*}
R_1 &= O \\
R_2 &= O
\end{align*}
\]

*Figure 1. Simplified structure of some oxides (left) and epoxide (right)*

The linoleum cement is then mixed with pine resin, rosin, cork, woodflour, chalk, clay and pigments to form sheets on a jute or hardened canvas backing. The figure below shows the ingredients used in linoleum.
This is then heated to 70 - 90°C in seasoning rooms, which accelerates the oxidation and consequently toughens the linoleum. The photograph below shows a roll of linoleum.

The linoleum is then seasoned for two to four weeks at this elevated temperature in the drying rooms.

### 2.4 Benefits of Linoleum as a Flooring Product

Linoleum can be manufactured entirely from renewable resources- linseed oil, rosin, wood floor, cork powder and pigments. Indoor air quality is becoming of increasing importance to consumers and this is less affected through the introduction of linoleum than vinyl (Advanced Buildings, 2005).

Since the colouring of linoleum goes through the entire surface, the design can continue to be seen as the product wears away. Scratches can be disguised or erased by abrading the surface to a smooth finish.
Linoleum does not burn readily, or absorb liquids, making it extremely suitable for areas such as kitchens. It can therefore be mopped and scrubbed using conventional detergents even in high traffic areas. It does not generate static electricity (Green Floors, 2005).

During use, linoleum does not require the addition of anti-bacterial agents, as this feature is inherent in the product. It is naturally antimicrobial and inhibits the growth and spread of microbes (iFloor, 2006).

At the end-of-life the material will ultimately biodegrade and does not give off any hazardous emissions during decomposition. Incineration is also a viable option for disposal as linoleum has a similar calorific value to coal (18.6 MJ/kg) and the amount of CO2 given off during this process is similar to that taken up during growth of the natural raw materials (Green Floors, 2005).

2.5 Conclusion

Linoleum is useful as an environmentally preferable material to other flooring such as vinyl flooring. There are a number of benefits to its use that have been described above.

The drawback with the production of linoleum is the time taken for manufacture; the oxidising process can take several weeks. Epoxidising the linseed oil can result in a more reactive product that will cure quickly. However, the properties of the final product will differ.

Linoleum is also limited in design and in the late-twentieth century endured a reputation as budget flooring low on style and high on practicality. Linoleum is not a high fashion product and may yet have a revival of fortune in the 21st century under the environmental umbrella.

It can be seen that the chemistry used in the manufacture of linoleum is different to that used in the production of PAF. The time taken for the manufacturing process of linoleum is not consistent with the PAF concept and therefore this process cannot be used.

However, the bio-resin may be used in a current industrial process at Interface. If the bio-resin is to be used in this way, that process must first be described and understood. This is described in the next chapter.
3 The Manufacture of PVC-backed Carpet Tile

3.1 Introduction

The 24-month report described the possibility of using the bio-resin in a current Interface product- Interlock. This showed that there was a great deal more understanding to be completed before this substitution could take place. However, there are other applications in which this product may be used. One such example is as part of a backing system. This system is described in this chapter.

There are a number of systems available for backing carpet before cutting into carpet tiles, two of which are used at Shelf Mills. They are known as Graphlex and Glasbac. The Graphlex backing has been described in earlier reports as recycled filler was investigated as a potential substitute in this system (Carter, 2005).

It is a patented system that is a carbon polymerised composite incorporating layers of fibreglass. The fibreglass is multidirectional and therefore its main purpose is to offer dimensional stability. It is desirable that the backing system be relatively heavy so that it will not warp, wrinkle or dome under heavy traffic or extreme changes in humidity and temperature.

The result is a backing that contains, by weight, 3% fibreglass, 1-2% fleece and over 95% bitumen mix (33% pre-modified bitumen, 67% filler). The bitumen is applied hot and cooled to allow it to set.

![Image of Graphlex backing system](https://example.com/graphlex-backing-system.png)

*Figure 1. Illustration of Graphlex backing system (Interface Europe, Backing Systems, 2003)*
The Glasbac system is a thermoplastic composite that again incorporates fibreglass for dimensional stability. However the primary backing constituent is based on plasticized and filled polyvinyl chloride (PVC). It is applied cool and heated to cure.

![Diagram of GlasBac backing system](image)

**Figure 2. Illustration of GlasBac backing system (Interface Europe, Backing Systems, 2003)**

There are several ways in which to replace the current thermoplastic material with one of lesser environmental impact. A substitute material may require different processing conditions and most of these will impact on the current processing requirements. Therefore the current processing must first be assessed.

PVC is manufactured from vinyl chloride (CH₂=CHCl), although it can be heavily plasticised and additives such as flame-retardants, stabilisers, pigments and fillers are usually added. It is a thermoplastic and therefore can be heated and cooled to form different shapes. Heat is required in this instance to cure the PVC due to the additives included.

### 3.2 Preparation of PVC mix

PVC is an expensive polymer and therefore must be filled with more cost effective materials. It is mixed with plasticizers, resins and fillers in order to bulk the mix. The plasticizers and resins allow more filler to be added. In the case of Interface, the filler used is graded virgin limestone.
3.3 Application of the Backing System

As well as considering the attributes that are offered by a floor, it is important to establish the current processing conditions of the PVC backing before considering a replacement system. This chapter describes the current conditions for the established product and operating constraints. In this section the operating limits of the equipment are also established in order to understand processing restrictions within the current equipment.

The tufted top cloth will normally have already been pre-coated with an adhesive system before it is processed with the Glassbac system. This pre-coating takes place in the same manufacturing site. There are different compounds applied, depending on the yarn system used.

The tufted top cloth is presented in a continuous roll via the use of a sewing system. The end of the roll being processed is attached to the beginning of the next using an adhesive strip. It is heated to around 160°C (± 5°C). This temperature can be varied from room temperature to over 200°C. This is shown in figure 3 and 4 below.

![Figure 3. Application of adhesive to join rolls](image)

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The tufted topcloth is wound into bins to store the excess which ensures that the remainder of the processes can take place continuously. The tension on the pre-coated system can be altered to allow for different systems of face yarn.

The pre-coated tufted cloth is then presented at PVC Station 1 (figure 5). At this point, room temperature PVC mix is applied to the back of the cloth. It is delivered via 1.5 tonne batches from the PVC compounding site. At the PVC compounding facility the PVC is mixed with fillers, additives and plastisol. The amount and type will depend on the customer requirements.
A levelled blade controls the amount of PVC mix applied. This can be raised or lowered depending on the thickness of the top cloth and the amount of PVC mix required. The flow-rate of PVC mix depends on the opening of the taps, which is done by hand.

At PVC Station 2 a sheet of fibreglass is coated with PVC mix in the same manner, although here it is thicker to avoid the PVC mix striking through to the top cloth, again at room temperature. The two sheets are then sandwiched together, with the PVC mix in between, as shown in figure 6.

![Figure 6. Schematic of fibreglass and tufted yarn systems forming sandwich with PVC mix](image)

The drum is heated to 160 °C for most applications of PVC. This aids the cure of the PVC before another layer of fibreglass and PVC is added. The temperature of the drum can be varied between room temperature and 200 °C, within 1 °C increments. However, the range of temperatures it is typically used at is from 150 °C to 170 °C.

The sandwich is then taken to Station 3 where a further layer of PVC is applied. Again here the thickness of PVC that is applied can be altered through the use of a levelled blade. The entire system is then sent to an oven (figure 7) to accelerate cure.
Figure 7. Radiant panel heating aiding cure of PVC

The oven is typically held at 160 - 180 °C, although it can be lowered to room temperature if required when there is a stoppage in the line. The PVC is not in direct contact with any heat as it is applied through radiation. A camera is used to measure the surface temperature of the carpet, and the information is used to control the output of an infrared heater.

On removal from the oven an embossing roller applies a pattern to the PVC (figure 8). This pattern is set as the system is then cooled on two cooling drums, which are kept cool through the use of chilled water.

Figure 8. Embossing applied to the back of the system
Once the system is cool, details of the particular carpet tile and other order specifications are printed over the embossing. The tiles are then cut out using a press.

The line speed can be altered depending on requirements, up to 10 m/min in 0.1 m/min increments. It is typically held at around 5 m/min.

3.4 Summary

Although the manufacture of the Glasbac system has strict requirements, depending on the specifications required for the product, there is scope for varying the processing requirements. For example, the temperature of the heated rolls, cooling rolls and infrared heater can be varied. Altering the line speed can also vary the time taken to heat the material.

The PVC is applied cool and this cannot be altered without some investment in capital costs. Therefore a liquid system is preferable for straightforward replacement. The system can then be heated and cooled in a number of ways without excess modifications.

It can be concluded that the PVC application system may be modified such that a different material may be used. However, this material would need to offer similar properties to PVC both in processing and use. These would be processing times, residence times, viscosity at application and cost.
4 Manufacture of Cross-linker for Bio-Resin

4.1 Introduction

The 2-year dissertation describes the concept of ‘Sustainable’ Interlock and Pour-A-Flor (PAF). These are innovative concepts for flooring solutions, based on the use of renewable technologies.

The concept of PAF is based on the premise that a liquid can convert to a solid in-situ. There are several ways in which this can be achieved, for example:

- Solidification of a melt on cooling
- Drying due to evaporation of a liquid phase from a solution in which the solid phase is dispersed
- Drying due to the evaporation of a solvent
- Polymerisation of a monomer or mixture of monomers (bulk, solution, suspension, emulsion etc)
- Cross-linking of a partly polymerised system
- Phase reversal of solid dispersed in a liquid phase to give a solution of the liquid in the solid.

The concepts described in previous reports have been based on the polymerisation of a liquid epoxidised linseed oil (ELO). The initial investigation that focused on reducing the time taken for this reaction is described in the 2-year dissertation.

This chapter describes the production of a di-acid that is used to cross-link ELO. It is included here in order to understand the source of the bio-resin. The description also shows that the production of the di-acid is relatively simple and may potentially be scaled up to commercial production.

4.2 Production of Di-acid- Basic Theory

The cross-linking of an ELO is achieved via the use of a liquid di-acid to form a flexible polymer network, shown in figures 1, 2 and 3 below.

![Figure 1. Simplified chemical structure of ELO](image-url)
The reaction can occur in around 15 minutes at 150°C, although this does result in slight yellowing. They can simply be mixed together at room temperature and allowed to cure, although this process can take days.

There are no other products emitted during the reaction that need to be disposed of.

This process that forms the cross-linker is of interest as ultimately, the entire lifecycle of the polymer will be studied. It is important that there are no health and safety risks that preclude the development of the polymer with this cross-linker. This process will be studied here

In order to function, the cross-linker must have two reactive groups, one on each end. If there were a single group, the polymerisation would not be able to proliferate and long chains would not form. These reactive groups are acid groups that react with the epoxy groups in the ELO.

These acid groups are formed from a previous reaction of dipropylene glycol with maleic anhydride.
Figure 4. Di-acid formed by heating di-ether in the presence of maleic anhydride

There are two mols of maleic anhydride required per mol of dipropylene glycol.

The molecular weight of maleic anhydride (MA) can be calculated as 98.06 g/mol and dipropylene glycol (DG) as 134.18 g/mol.

Therefore the mass ratios required are

\[ \text{MA : DG} = 2 \times 98.06 : 134.18 = 196.12 : 134.18 = 1.46 : 1 \]

4.3 Production of the Di-acid on a Laboratory Scale

4.3.1 Constituents

Maleic anhydride is a white, pungent solid at room temperature. It has a tendency to sublime and therefore must be handled carefully. It is often in the form of white flakes or blocks that melt at 52 – 55 °C.

Dipropylene glycol is a clear odourless liquid at room temperature. It boils at 229 – 232 °C.

The constituents are shown in figure 5 below.

Figure 5. Maleic anhydride and Dipropylene glycol
The constituents can be mixed at room temperature with no visible reaction occurring and can be temporarily stored in this form until required. The DG provides a seal to the atmosphere that should prevent sublimation. However once the reaction begins and stirring takes place, the MA will be exposed to the atmosphere intermittently and therefore the vessel should be sealed to prevent the MA sublimating and being lost to the local environment.

The safety data sheets for 99% dipropylene glycol and 99% maleic anhydride are given in Appendix A and B. These are courtesy of Fisher Scientific. These should be adhered to at all times.

Basic precautions are to avoid inhalation or swallowing of either constituent. Wear protective gloves, goggles and overall at all times.

4.3.2 Experimental Method

A large, round-bottomed flask is selected and maleic anhydride with dipropylene glycol is placed in the bottom as shown schematically in figure 6 below.

![Figure 6. Schematic set-up of apparatus](image-url)
Once the constituents are inserted into the flask, they are sealed to the atmosphere and the vessel purged with nitrogen. The cotton wool is inserted into the bottom of the allihn condenser in order to reduce the amount of MA given off to the atmosphere, whilst allowing the nitrogen to pass. The cotton wool aids the solidification of the MA closer to the vessel, which in turn allows the MA to sublimate back into the vessel.

A heating mantle is required to heat the mixture to around 95 °C (± 5 °C) and the mixture is continuously stirred. Careful heating and cooling cycles are applied as required in order to maintain a consistent temperature as the reaction has a tendency to be exothermic at this temperature.

The mixture will also tend to cross-link with itself above temperatures of 150 °C and result in a viscous mass that will cool to a solid.

The reaction is allowed to continue for 2 hours and 45 minutes, after which it is allowed to cool to room temperature.

4.3.3 Results and Discussion

1519.78 g of maleic anhydride (15.5 mols) was crushed and inserted into a 5 litre round-bottomed flask. 1039.82 g of dipropylene glycol (7.75 mols) was also added to the flask (figure 6). The resulting mixture looked as shown in figure 7.

![Figure 7. Resulting mixture in flask](image)

The apparatus was then set up as shown in the schematic (figure 6) and stirring began (figure 8)
Nitrogen was bubbled through the mixture and expunged via the condenser, within a fume extraction cupboard. The stirrer rotated at 120 rpm as the heater began to heat.

The figure below shows the mixture at 45 °C, clearly showing the maleic anhydride subliming onto the glass surface.

Figure 8. Apparatus set up

Figure 9. Mixture at 45 °C, continuing to heat
At 85 °C, after 45 minutes, the stirring was increased to 500 rpm as the maleic anhydride had mostly transformed to a liquid state. The tendency of the MA to sublime was still evident, although this was subsequently reduced through heating the walls of the glass vessel.

*Figure 10. Mixture at 85 °C*

After 55 minutes, at 95 °C, the mixture was allowed to cool via air and the addition of a water bowl. A careful heating and cooling cycle kept the mixture with 5 °C of this temperature. Sublimed material was still evident on the walls of the glass vessel (see below).

*Figure 11. Reaction continuing exothermically*
The temperature of the mixture became stable 1 hour and 40 minutes after the heating began. A tin foil jacket was then used to rid the vessel of sublimated MA, which in turn encouraged the last of the reaction to take place. This was then left to cool with continuous stirring for a further 1 hour and 50 minutes (figure 12).

*Figure 12. Thermal jacket surrounding completed reaction*

The resulting mixture is a fairly viscous, clear, liquid that will be used to cross-link the ELO.

It can be seen that the chemistry of this reaction is relatively simple to achieve. There are a series of precautions that need to be taken in order to reduce the risk to the user and local environment. However, if these are followed correctly then there will be no adverse effects to local organisms.

It has been shown that the temperature of the reaction needs to be controlled carefully in order to create the product required. This is something that will require careful consideration for increased volumes of production.

Analysis has also shown that, although the reaction is mostly complete after 1 hour and 45 minutes, continuing for the further 1 hour ensures that all the constituents are reacted.
The cross-linker is produced from two elements with the possibility that one of these may be made from renewable resources and this requires further investigation, perhaps via the use of the Green Chemistry Network.

4.4 Concluding Remarks

The cross-linker is relatively simple to produce from two components, with careful consideration of emissions, temperature and health and safety. The reaction may be scaled up or down to produce different quantities of cross-linker.

The cross-linker will be used in a reaction to produce a resin based on renewable resources. However, there are other cross-linkers that may be considered for future use which are described in the 2-year dissertation. This cross-linker is chosen to be investigated further as it does not necessarily require the input of energy to activate the cross-linking reaction.

The next chapter describes the process of investigating the effect of varying the amount of cross-linker used in curing the ELO.
5 Experimental Methods

5.1 Introduction

In order to be able to decide if a material can replace PVC in any capacity, it must be deemed ‘fit-for-purpose’, i.e. it must perform as designed in service without undue failure. In the particular example of a flooring product it must perform as a stable surface without undue risk to the user. There are other considerations such as health and safety in use, environmental performance, resistance to wear etc. The identification of these parameters is described in the 24-month report (Carter, 2005).

The purpose of the standard flooring material tests is to simulate conditions that occur in service. The standard tests include a castor chair test, simulating office use (BS EN 905:1994), Vetterman drum simulating footfall (BS ISO 10361:2000) and Lisson Tretrad simulating dry abrasion (BS EN 1963:1998). The tests typically used for carpet are more fully described in the 6-month report (Carter, 2004).

While these flooring tests are useful in simulating service conditions, around 0.25 m² of material is required per test. In many situations this is not a problem, but if we consider the bio-resin, then the associated material cost becomes important.

As the preliminary research was conducted in partnership with Agrotechnology and Food Innovations (A and F), there are significant costs associated with the manufacture of the cross-linker as described in Chapter 4. Although the manufacturing process is relatively simple, it is not currently possible to do this process at Interface, Shelf Mills. The cost is for the expertise and confidentiality of A and F and not the actual manufacturing process.

In future, larger scale experiments it would be prudent to scope out another supplier of the cross-linker that may be able to manufacture on a larger scale. However, at present, confidentiality issues prohibit this.

If we assume that each batch of tests would require at least 1 m² of material, then much of the cost is the cross-linker (1900 €/5kg), and assuming an average weight ratio of 0.7:1 (Diacid:ELO) and an average mass of 2 kg/m² we find that:

Cost per sample = 1 x (1900/5) x (0.7/1.7) x 2 = 313 € per sample

The cost becomes significant when large samples are used, and so it is beneficial to have some intermediate tests, the results from which can be used to give some indication of performance in service.
It has been proposed (Carter, 2006), that material indices (Ashby 2000, p407) can be related to performance in testing. However, the relationship between material characteristics and flooring performance is not yet fully understood. It is clear that harder and stronger materials are more durable in service. This is why materials such as varnished wood, ceramics, linoleum and nylon are used for flooring products, and rarely materials such as paper, foams and cotton.

The bio-resin has a number of process parameters in manufacture, such as cross-linker amount, time at elevated temperature and temperature, that may affect the performance in service as well as the material characteristics. It is suggested that the properties determined from a sample tensile test may highlight differences in material characteristics relevant to flooring performance without requiring a large volume of material to undergo testing.

Traditional flooring tests will then be carried out on the materials identified from this preliminary case study, in order to assess if these differences highlighted by the tensile tests are indeed exhibited during simulated use.

5.2 Test Method

There are a number of ways in which to determine material properties. As an example, the most common method for determining Young's Modulus (E) and strength (\(\sigma\)) is a tensile test using a tensile tester such as a Testometric Micro 350.

This involves taking a sample of known dimensions and applying a force, or continuous movement until the sample fails. The resulting graph of force versus distance moved can be converted into a nominal stress-strain graph (figure 1).

Since:

\[
\sigma = \frac{F}{A}
\]

where \(F\) is the force applied and \(A\) is the nominal cross-sectional area.

And strain (\(\varepsilon\)):

\[
\varepsilon = \frac{\delta l}{l}
\]

where \(\delta l\) is the extension measured over the initial gauge length, \(l\).

From the graph, the properties of modulus, \(\sigma_y\) (yield stress) and \(\sigma_f\) can then be determined (see figure 1).
Figure 1. Schematic stress-strain curve

This is just one example of tests that are available to determine material properties and is the one that will be used for the preliminary testing.

5.3 Sample Preparation

The samples to be used in the tensile tests need to be (and are) prepared in a manner that can be consistently repeated and reproduced. Therefore it is important that the sample preparation is documented. The manner in which the samples are prepared for testing is adapted from several British Standards.

A disposable compatible container is used to hold the constituents. The cross-linker is first placed within a container and the mass measured using a calibrated scale-the Mettler P1200, correct to ±0.01 g. The epoxidised linseed oil (ELO) is then added to the cross-linker. As it is less viscous than the cross-linker its addition is easier to control. The molar ratio of components is noted and mass ratio calculated-the exact amount added is carefully controlled and noted in a log. It is subsequently used to calculate the exact molar ratio of components.

Any other additions that are required for the mix are added after the main components. The components are then well mixed using a magnetic stirrer at 3000 rpm for 2 minutes. This speed and time were chosen as it has previously been shown to provide an effective mix (A and F, 2005). This speed and time were also used in previous experiments in which a vegetable dye was added and visual inspection suggested that the dye was distributed evenly after 2 minutes of stirring.
The mould to be used is pre-heated in an oven to 5°C above the desired temperature. The elevated temperature is required as there is a temperature fall when the oven door is opened. The mould is removed, the liquid poured into the mould and then replaced in the oven. However, immediately upon returning the mould to the oven, the temperature is reset to the desired value with a variance of ±1 °C. This is set using a calibrated digital control.

A tensile specimen mould was manufactured from stainless steel to the dimensions set out in BS EN ISO 527-2: 1996 (figure 2). Early experiments with the component mix and a tensile test mould showed that lubrication was essential to ensure the sample could be released.

However, there was no method of lubrication that could be found for the mould, shown below, that allowed easy release of the specimen without mechanical deformation.

![Figure 2. Tensile test specimen mould filled with material](image)

Therefore it was decided that the samples required should be cut from sheet material- regretfully using more material and providing more waste. However, this could be minimised using a careful cutting regime.

The component mix is therefore poured into a heavy tray with a non-stick surface or non-stick liner (figure 3). This tray is pre-heated in the oven to 5 °C above the required temperature and care is taken to ensure that it is level in the oven. The tray will also lose heat when the oven door is opened.
The mixture is poured quickly into the tray and returned to the heated oven for the required time. Small amounts of bubbles are still present from the mixing procedure, although the amount of air is minimised through the mixing procedure used. The bubbles disperse quickly on heating of the mixture.

After the required amount of time, the tray is removed from the oven and the sample is removed from the tray. It is placed on a wire rack in order to allow full air circulation at room temperature. It is then labelled in the following manner:

00.00/111/22x/AAA/Y

In this labelling system 00.00 is the molar ratio of diacid to 1 mole of ELO, 111 is the curing temperature in °C, 22x is the curing time in hours or minutes (given by x), AAA are available for other additions and Y indicates the sample letter- A, B, C etc.

There are no British Standards that describe the conditioning required for this particular system. However, there are examples within the standards for other plastics and these are used here.

The sample is then left at room temperature for 72 hours. This ensures that any resilient processes have completed in accordance with BS EN ISO 1798:1999.

The sample is then cut out using a hand press and cutter (figure 4 and 5). This cutter has been specified by BS EN ISO 1798.
The cut samples must also be conditioned for 24 hours to ensure that the atmospheric effects are the same with each test. Depending on material, different requirements are placed on atmospheric conditions. A controlled atmosphere is used for traditional carpet tests of 65 ±5 % RH and 20 ± 1 °C. It therefore seems prudent to use this conditioning for the samples in each case, as well as testing in this environment.

For each set of samples, at least six samples are produced- this is to ensure that there are five samples that are suitable for testing, as specified in BS 2846-2:1981 ISO 2602-1980. The samples are individually labeled in the same manner as before and are then ready for testing.

### 5.4 Testing

“This British Standard describes the determination of tensile properties of plastics, including general principles. The methods described in this standard are used to investigate the tensile behaviour of the test specimens and for determining the tensile strength, tensile modulus and other aspects of the tensile stress/strain relationship under the conditions defined.”

After cleaning off any loose particles, the central portion of the dumbbell is measured across the width and thickness to ± 0.1 mm. Three measurements are taken and the arithmetic mean value for the width and thickness calculated. Five samples are measured in turn and the results logged.

The gauge length is marked on the samples, approximately equidistant from the mid-point, not more than 50 mm ± 1 mm apart (EN ISO 1798:1999).

The test specimen is then clamped in the Testometric Micro 350 (figure 6), calibrated by UKAS to ISO 5893 and BS EN ISO 7500-1:1999 to grade 0.5, taking care to align the longitudinal axis of the test specimen with the axis of the testing machine and to set the gauge length correctly.

Figure 6. Testometric Micro 350

The stiffness of the machine has been calculated by the manufacturers and is accounted for in the electronic calculation of the distance moved by the crosshead.
The test specimen is extended along its major longitudinal axis at a constant speed of 100 mm/min until the specimen fractures. Any fractures that occur outside the gauge length, within 10 mm of the jaws or where there is an obvious defect are discarded.

The maximum force and elongation is measured electronically using the Testometric Micro 350 and a stress-strain graph is produced.

The Young’s modulus of elasticity is calculated from the stress at a strain of 0.0005 and the stress at a strain of 0.0025 (i.e. a secant modulus between 0.05 and 0.25% strain). This is given in BS EN ISO 527-1:1996.

These calculations can be worked out for each of the samples and the arithmetic mean and standard deviation can be found. These results are then tabulated.

5.5 Results

The experiments are ongoing at present. The variables of interest are the effects of changing molar ratio of ELO: di-acid, temperature of cure and time of cure. A likely next step will be to assess the effects of adding filler.

Three samples were taken at a 2.5:1 (diacid:ELO) molar ratio and cured for 30 minutes at 140 °C, 150 °C and 160 °C.

From the data shown in figure 7 it is clear that there are marked differences in the mean nominal strain to failure, maximum nominal stress and Young’s Modulus. The error bars on the graph show the standard deviation of the results.
5.6 Conclusion

It can be seen from the preliminary results that there are measurable differences in some characteristics with experimental variables.

In order to conclude if these results are indicative of performance in service they must be compared with results from flooring tests. Therefore the experiments currently being undertaken will continue, with two extremes of performance tested in flooring tests.

If there is little or no difference in performance noted, then the preliminary tests will be invalid for their purpose. However, this would indicate that some other preliminary testing is required.

If there is correlation between this preliminary testing and performance in practice, this correlation can be assessed.
6 Future Work

The Gantt chart in figure one shows predicted progress for the next 18 months.

Samples will be manufactured with differing ratios of ELO:Diacid and also for different lengths of time at elevated temperature. Filler will also be added to the samples and differences in material properties (E, ε, σ) noted.

In order to establish if differences in these properties are significant, two samples will be tested using typical flooring tests, such as Vetterman drum (BS ISO 10361:2000) and Lisson Tretrad (BS EN 1963:1998).

These samples will be chosen for their different material characteristics as extremes of performance. It will be intriguing to note if there are different performances in these flooring tests.

If there are no differences in performance then it can be established that the tensile tests are not indicative. In this case, a full regiment of tests will be required to test the effect of each manufacturing variable.
Figure 1. Gantt chart for next 18-Month period
Appendix A

Safety Data Sheet

DIPROPYLENE GLYCOL, 99% MIXTURE OF ISOMERIC PROPYLENE GLYCOL ETHERS

Section 1 - Chemical Product and Company Identification

MSDS Name: DIPROPYLENE GLYCOL, 99% MIXTURE OF ISOMERIC PROPYLENE GLYCOL ETHERS
Catalog Numbers: 40915-0000, 40915-0010, 40915-0250
Synonyms:
Company Identification: Acros Organics BVBA
                     Janssen Pharmaceuticaalaa
                     3a
                     2440 Geel, Belgium
Company Identification: (USA) Acros Organics
                       One Reagent Lane
                       Fair Lawn, NJ 07410
For information in the US, call: 800-ACROS-01
For information in Europe, call: +32 14 57 52 11
Emergency Number, Europe: +32 14 57 52 99
Emergency Number US: 201-796-7100
CHEMTREC Phone Number, US: 800-424-9300
CHEMTREC Phone Number, Europe: 703-527-3887

Section 2 - Composition, Information on Ingredients

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Hazard Symbols: None listed.

Dipropylene Glycol
Appendix A

**Risk Phrases:** None listed.

### Section 3 - Hazards Identification

**Emergency Overview**

*Not available.*

**Potential Health Effects**

- **Eye:** Causes mild eye irritation.
- **Skin:** Causes mild skin irritation.
- **Ingestion:** Expected to be a low ingestion hazard.
- **Inhalation:** May cause respiratory tract irritation.
- **Chronic:** Prolonged or repeated exposure may cause nausea, dizziness, and headache.

### Section 4 - First Aid Measures

- **Eyes:** Flush eyes with plenty of water for at least 15 minutes, occasionally lifting the upper and lower eyelids. Get medical aid.
- **Skin:** Get medical aid. Flush skin with plenty of water for at least 15 minutes while removing contaminated clothing and shoes.
- **Ingestion:** Get medical aid. Wash mouth out with water.
- **Inhalation:** Remove from exposure and move to fresh air immediately. Get medical aid.

**Notes to Physician:**

### Section 5 - Fire Fighting Measures

**General Information:** As in any fire, wear a self-contained breathing apparatus in pressure-demand, MSHA/NIOSH (approved or equivalent), and Dipropylene Glycol.

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Appendix A

full protective gear.

**Extinguishing Media:** Use water spray, dry chemical, carbon dioxide, or chemical foam.

**Section 6 - Accidental Release Measures**

**General Information:** Use proper personal protective equipment as indicated in Section 8.

**Spills/Leaks:** Absorb spill with inert material (e.g. vermiculite, sand or earth), then place in suitable container.

**Section 7 - Handling and Storage**

**Handling:** Avoid breathing dust, vapor, mist, or gas. Avoid contact with skin and eyes.

**Storage:** Store in a cool, dry place. Store in a tightly closed container.

**Section 8 - Exposure Controls, Personal Protection**

**Engineering Controls:** Use adequate ventilation to keep airborne concentrations low.

**Exposure Limits**

CAS# 25265-71-8:

**Personal Protective Equipment**

**Eyes:** Wear chemical splash goggles. Wear appropriate protective eyeglasses or chemical safety goggles as described by OSHA’s eye and face protection regulations in 29 CFR 1910.133 or European Standard EN166.

**Skin:** Wear appropriate protective gloves to prevent skin exposure.

**Clothing:** Wear appropriate protective clothing to prevent skin exposure.

Dipropylene Glycol
Respirators: Follow the OSHA respirator regulations found in 29 CFR 1910.134 or European Standard EN 149. Always use a NIOSH or European Standard EN 149 approved respirator when necessary.

Section 9 - Physical and Chemical Properties

Physical State: Clear liquid
Color: colorless - APHA: 15 max
Odor: Not available.
pH: Not available.
Vapor Pressure: Not available.
Viscosity: Not available.
Boiling Point: 229 - 232 deg C @ 760.00 mm Hg
Freezing/Melting Point: Not available.
Autoignition Temperature: 310 deg C (590.00 deg F)
Flash Point: 138 deg C (280.40 deg F)
Explosion Limits: Lower: 2.90 vol %
Explosion Limits: Upper: 12.60 vol %
Decomposition Temperature:
Solubility in water: miscible with water
Specific Gravity/Density: 1.0200g/cm3
Molecular Formula: C6H14O3
Molecular Weight 134.18

Section 10 - Stability and Reactivity

Chemical Stability: Stable under normal temperatures and pressures.
Conditions to Avoid: Incompatible materials.
Incompatibilities with Other Materials: Strong oxidizing agents.
Hazardous Decomposition: Carbon monoxide, carbon
Dipropylene Glycol
Appendix A

**Products**
dioxide.

**Hazardous Polymerization**
Will not occur.

---

**Section 11 - Toxicological Information**

**RTECS#:** CAS# 25265-71-8: UB8765000

**LD50/LC50:**
- CAS# 25265-71-8: Oral, rat: LD50 = 14850 mg/kg; Skin, rabbit: LD50 = >20 mL/kg; <BR. Skin, rabbit: 500 mg/24H mild Eye, rabbit: 500 mg mild

**Carcinogenicity:** DIPROPYLENE GLYCOL - Not listed as a carcinogen by ACGIH, IARC, or NTP.

**Other:** See actual entry in RTECS for complete information.

---

**Section 12 - Ecological Information**

**Other:** No information available.

---

**Section 13 - Disposal Considerations**

Dispose of in a manner consistent with federal, state, and local regulations.

---

**Section 14 - Transport Information**

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**Shipping Name:** Dipropylene Glycol

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Section 15 - Regulatory Information

European/International Regulations

European Labeling in Accordance with EC Directives

Hazard Symbols: Not available.

Risk Phrases:

Safety Phrases:
S 24/25 Avoid contact with skin and eyes.

WGK (Water Danger/Protection)

CAS# 25265-71-8: 1

Canada

CAS# 25265-71-8 is listed on Canada's DSL List

US Federal

TSCA

CAS# 25265-71-8 is listed on the TSCA Inventory.

Section 16 - Other Information

MSDS Creation Date: 8/02/1996
Revision #1 Date 4/11/2000

The information above is believed to be accurate and represents the best information currently available to us. However, we make no warranty of merchantability or any other warranty, express or implied, with respect to such information, and we assume no liability resulting from its use. Users should make their own investigations to determine the suitability of the information for their particular purposes. In no event shall Fisher liable for any claims, losses, or damages of any third party or for lost profits or any special, indirect, incidental, consequential, or exemplary

Dipropylene Glycol

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Appendix A

damages howsoever arising, even if Fisher has been advised of the possibility of such damages.

Dipropylene Glycol
Appendix B

Safety Data Sheet

Section 1 - Chemical Product and Company Identification

MSDS Name: Maleic anhydride, 99%
Catalog Numbers: 36494-0000, 36494-0010, 36494-0050,
Synonyms: 36494-0250

Company Identification: Acros Organics BVBA
Janssen Pharmaceuticaalnaan
3a
2440 Geel, Belgium

Company Identification: (USA) Acros Organics
One Reagent Lane
Fair Lawn, NJ 07410

For information in the US, call: 800-ACROS-01
For information in Europe, call: +32 14 57 52 11
Emergency Number, Europe: +32 14 57 52 99
Emergency Number US: 201-796-7100
CHEMTREC Phone Number, US: 800-424-9300
CHEMTREC Phone Number, Europe: 703-527-3887

Section 2 - Composition, Information on Ingredients

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Hazard Symbols: C

Risk Phrases: 22 34 42/43

Maleic Anydride

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Appendix B

Section 3 - Hazards Identification

EMERGENCY OVERVIEW

Harmful if swallowed. Causes burns. May cause sensitization by inhalation and skin contact. Moisture sensitive.

Potential Health Effects

Eye: Causes eye burns. May cause conjunctivitis. Causes redness and pain.

Skin: Causes skin burns. May cause skin sensitization, an allergic reaction, which becomes evident upon re-exposure to this material. Causes redness and pain. May cause blistering of the skin.

Ingestion: Harmful if swallowed. Causes gastrointestinal tract burns.

Inhalation: May cause allergic respiratory reaction. May cause irritation of the respiratory tract with burning pain in the nose and throat, coughing, wheezing, shortness of breath and pulmonary edema. Causes chemical burns to the respiratory tract.

Chronic: Repeated exposure may cause allergic respiratory reaction (asthma). Prolonged or repeated contact may cause possible eczema.

Section 4 - First Aid Measures

Eyes: Immediately flush eyes with plenty of water for at least 15 minutes, occasionally lifting the upper and lower eyelids. Get medical aid immediately.

Skin: Get medical aid immediately. Immediately flush skin with plenty of water for at least 15 minutes while removing contaminated clothing and shoes.

Ingestion: Get medical aid immediately. Wash mouth out with water.

Maleic Anydride
**Appendix B**

**Inhalation:** Get medical aid immediately. Remove from exposure and move to fresh air immediately. If not breathing, give artificial respiration. If breathing is difficult, give oxygen.

**Notes to Physician:** Treat symptomatically and supportively.

---

**Section 5 - Fire Fighting Measures**

**General Information:** As in any fire, wear a self-contained breathing apparatus in pressure-demand, MSHA/NIOSH (approved or equivalent), and full protective gear. Dusts at sufficient concentrations can form explosive mixtures with air.

**Extinguishing Media:** Use carbon dioxide. Use alcohol foam. Do NOT use dry powder.

---

**Section 6 - Accidental Release Measures**

**General Information:** Use proper personal protective equipment as indicated in Section 8.

**Spills/Leaks:** Vacuum or sweep up material and place into a suitable disposal container.

---

**Section 7 - Handling and Storage**

**Handling:** Avoid breathing dust, vapor, mist, or gas. Avoid contact with skin and eyes. Take precautionary measures against static discharges.

**Storage:** Store in a cool, dry place. Store in a tightly closed container. Store protected from moisture.

---

**Section 8 - Exposure Controls, Personal Protection**

**Engineering Controls:** Facilities storing or utilizing this material should be

Maleic Anydride
equipped with an eyewash facility and a safety shower. Use adequate ventilation to keep airborne concentrations low.

**Exposure Limits**

**CAS# 108-31-6:**

- United States OSHA: 0.25 ppm TWA; 1 mg/m^3^ TWA
- Belgium - TWA: 0.25 ppm VLE; 1 mg/m^3^ VLE
- France - VLE: 1 mg/m^3^ VLE
- Germany: 0.1 ppm TWA; 0.41 mg/m^3^ TWA
- Malaysia: 0.25 ppm TWA; 10 mg/m^3^ TWA
- Netherlands: 0.1 ppm MAC; 0.4 mg/m^3^ MAC
- Russia: 1 mg/m^3^ TWA

**Personal Protective Equipment**

- **Eyes:** Wear chemical splash goggies.
- **Skin:** Wear appropriate protective gloves to prevent skin exposure.
- **Clothing:** Wear appropriate protective clothing to prevent skin exposure.
- **Respirators:** Follow the OSHA respirator regulations found in 29 CFR 1910.134 or European Standard EN 149. Always use a NIOSH or European Standard EN 149 approved respirator when necessary.

**Section 9 - Physical and Chemical Properties**

- **Physical State:** Flakes
- **Color:** white

Maleic Anydride
Appendix B

**Odor:** pungent odor

**pH:** Not available.

**Vapor Pressure:** 0.16 mm Hg @ 20 deg C

**Viscosity:** 1.6 mPa.s @ 60 deg C

**Boiling Point:** 200 deg C @ 760 mmHg (392.00°F)

**Freezing/Melting Point:** 52-55 deg C

**Autoignition Temperature:** 477 deg C (890.60 deg F)

**Flash Point:** 103 deg C (217.40 deg F)

**Explosion Limits: Lower:** 1.40 vol %

**Explosion Limits: Upper:** 7.10 vol %

**Decomposition Temperature:** >150 deg C

**Solubility in water:** 79g/100ml in water (25°C)

**Specific Gravity/Density:**

**Molecular Formula:** C₄H₂O₃

**Molecular Weight:** 98.06

Section 10 - Stability and Reactivity

**Chemical Stability:** Stable.

**Conditions to Avoid:** Incompatible materials, ignition sources, dust generation, exposure to moist air or water.

**Incompatibilities with Other Materials**

Strong oxidizing agents, strong reducing agents, strong acids, strong bases, alkali metals, alkaline earth metals, amines, caustics (e.g. ammonia, ammonium hydroxide, calcium hydroxide, potassium hydroxide, sodium hydroxide), triethylamine, pyridine, ammonium ions.

**Hazardous Decomposition Products**

Carbon monoxide, carbon dioxide.

**Hazardous Polymerization**

Will not occur.

Maleic Anydride
Appendix B

Section 11 - Toxicological Information

RTECS#: CAS# 108-31-6: ON3675000
LD50/LC50:

**CAS# 108-31-6**: Dermal, guinea pig: LD50 = >20 gm/kg; Draize test, rabbit, eye: 1% Severe; Oral, mouse: LD50 = 465 mg/kg; Oral, rabbit: LD50 = 875 mg/kg; Oral, rat: LD50 = 400 mg/kg; Skin, rabbit: LD50 = 2620 mg/kg;<BR.

**Carcinogenicity**: Maleic anhydride - Not listed as a carcinogen by ACGIH, IARC, or NTP.

**Other**: See actual entry in RTECS for complete information.

Section 12 - Ecological Information

**Ecotoxicity**: Fish: Mosquito Fish: LC50 = 240 mg/l; 96 H; . Fish: Bluegill/Sunfish: LC50 = 150 mg/l; 24 H; . Bacteria: Phytobacterium phosphoreum: EC50 = 44 ppm; 30 min.; Microtox test Daphnia: LC50 = 330 mg/l; 48 H; . Fish: Rainbow trout: LC50 = 75 mg/l; 96 H; .

**Other**: Do not empty into drains.

Section 13 - Disposal Considerations

Dispose of in a manner consistent with federal, state, and local regulations.

Section 14 - Transport Information

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Maleic Anhydride
Appendix B

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USA RQ: CAS# 108-31-6: 5000 lb final RQ; 2270 kg final RQ

## Section 15 - Regulatory Information

### European/International Regulations

European Labeling in Accordance with EC Directives

- **Hazard Symbols:** C
- **Risk Phrases:**
  - R 22 Harmful if swallowed.
  - R 34 Causes burns.
  - R 42/43 May cause sensitization by inhalation and skin contact.
- **Safety Phrases:**
  - S 22 Do not breathe dust.
  - S 26 In case of contact with eyes, rinse immediately with plenty of water and seek medical advice.
  - S 36/37/39 Wear suitable protective clothing, gloves and eye/face protection.
  - S 45 In case of accident or if you feel unwell, seek medical advice immediately (show the label where possible).

**WGK (Water Danger/Protection)**

- CAS# 108-31-6: 1

**Canada**

- CAS# 108-31-6 is listed on Canada's DSL List

**US Federal**

- TSCA

  - CAS# 108-31-6 is listed on the TSCA Inventory.

## Section 16 - Other Information

Maleic Anydride
Appendix B

**MSDS Creation Date:** 11/21/2001
**Revision #0 Date** Original.

Maleic Anydride
Dianne Carter

36-Month Report

01.04.06 - 01.10.06

"Towards Sustainable Design and Manufacture of Textile Flooring Products"
Abstract

The EngD project is looking at more sustainable flooring solutions in the context of Interface's goal to be a sustainable company by 2020.

Success has been in introducing renewable content into the current textile-flooring product. In a previous report (Carter, 2004) the introduction of recycled filler into the tile backing has shown that the Graphlex backing system can incorporate recycled material up to 67 wt%.

An innovation project Pour-A-Flor (PAF) was described and an initial investigation was conducted into the possibility of using a bio-resin within this concept. The preliminary investigation focused on measuring and then reducing the curing time of the resin.

The 32-month discussed other ways in which this resin system could be used within InterfaceFLOR. It was concluded that there were a number of ways in which this system may be used, whilst still heading for the goal of sustainability.

The investigation of the resin began with preliminary tensile tests to examine the effect of change of processing parameters on mechanical properties. These tests were designed as proxy tests.

In order to conclude if these results are indicative of performance in service they must be compared with results from flooring tests. Therefore the experimental results were compared with two extremes of performance tested in flooring tests. It was concluded that the tensile tests could provide some indication of flooring test results.

The experimental methods used in assessing the material properties of the ELO resin are described in this report. There are differences in characteristics observed due to manufacturing differences

The further work section describes in detail the work to be undertaken in the next twelve months, including the flooring tests. There is also a Gantt chart showing up to the 40-month reporting period.
1 Introduction

1.1 Summary of Work Described in the 32-Month Report

The bio-resin was first described in the 18-month report. It was introduced as a system that may be used for the Pour-A-Flor (PAF) concept. A major component of the resin is epoxidised linseed oil. It is cross-linked with a di-acid in order to cure. Although this can occur at room temperature, the time to cure is greatly reduced by elevated temperature (Carter, 2005).

The 24-month report described other ways in which this resin may be used at InterfaceFLOR.

The report described the manufacturing process for linoleum and compared the curing process of the two products, the bio-resin and linoleum. There are other factors that may be considered such as material properties, use in service, costs etc. However, the report focused on the curing process as it showed that the bio-resin technology is novel and distinct. The curing time exhibited for linoleum is simply not feasible for a concept such as PAF.

The manufacture of a PVC-backed carpet tile was also described in order to understand how the two processes differ, especially within manufacturing time constraints. This manufacturing process is also described in order to evaluate if the bio-resin may be used within the current process ideally with few modifications.

The experimental techniques used to assess the Young’s Modulus, nominal strain to failure and nominal peak stress of the bio-resin were also described.

1.2 Project Direction in the Current Reporting Period

The purpose of the tensile tests was to determine the effect on mechanical properties of altering the processing parameters. It was theorised that the mechanical properties are related to the performance in service. Therefore these tests could be used as proxy tests, using much less material and being faster to perform.

This report describes the investigation of the effect of individually changing molar ratio, cure temperature and cure time. These experiments are designed to show the effect of changing one processing parameter, whilst all others remain the same.
This report also describes the results of flooring tests on two samples that are compared to the Interlock sample— an InterfaceFLOR product manufactured from PVC currently in use. The results from the tensile tests and the flooring tests are then compared.

It was previously decided at the 24-month report that fillers could be advantageous in the manufacture of the resin product for a number of reasons, including reducing cost and altering properties further.

This report also describes an investigation into the waste streams currently being produced by InterfaceFLOR. The purpose of this investigation is to assess whether any of the waste streams being produced are viable as a filler for the PAF system.
2 Waste as Filler

2.1 Introduction

The main focus of this project has become the investigation of the Pour-A-Flor (PAF) system which is described further in Chapter 4. As part of this investigation, renewable fillers are being considered. This is in order to reduce both the environmental and economic impact of the product.

For consideration as filler for the PAF system a material must fulfil a number of criteria. These restrictions have been determined with the experience of dealing with the PAF system and recycled filler (Carter, 2005). It must:

- Be compatible with the constituents of the PAF system, i.e. it should be inert
- Be of small particle size (length less than 150 μm) to be homogeneously mixed in the material and applied using the PAF delivery system
- Be of low cost, i.e. pence per tonne
- Be readily available in large quantities
- Cause no harm to the environment- preferably being beneficial from a life cycle analysis point of view

It would be advantageous if the filler were bio-degradable at end-of-life or easily removed from the PAF system for recycling. The purpose of this chapter is to investigate the waste streams of InterfaceFLOR with a view to assessing whether the constituents could be used in the PAF system.

2.2 Closing the Loop

Previous reports at 6, 12 and 36 months have described the manufacturing process at InterfaceFLOR. These showed that the manufacture of a carpet tile was energy intensive and used a variety of materials. The current inputs include nylon, fibre-glass and bitumen.

As well as investigating alternative materials, InterfaceFLOR has committed itself to ‘closing the loop’- one of the principles adopted as part of the ‘Natural Step’ programme (Forum for the Future/ The Natural Step, 2006).

This involves changing from a linear manufacturing process of take-make-waste and adopting a cyclical process, which imitates that used by nature. In this system, the waste from one process becomes the input of another process and so material continues to be converted into useful product.
Practically, this becomes more difficult as the ease of recycling materials varies considerably. For example, some thermoplastics, such as polypropylene, can simply be melted and reformed for further use. However thermosets are intrinsically much more difficult to recycle as they need to be chemically disassembled into monomers first. This is an energy and chemical-intensive process. The monomers can then be re-joined to re-form the polymer in a useful guise (Society of Plastics Engineers, 2004). Some polymer chains will degrade during the recycling process, resulting in a progressively lower product with each cycle.

Often, impurities will be introduced when recycling material. This is a problem for industries that require a product of consistent standard and where impurities can be detrimental to performance. The impurities may be diluted with the addition of virgin raw material, as happens in the production of steel (Corus, 2006).

Therefore, the decision whether to recycle a material is actually a complex one. The Natural Step describes a range of factors that must be considered when determining how to ‘close the loop’:

- "Reuse of products, and product durability to enhance longevity, are of course the most resource-efficient first steps, and only then should recycling be considered.
- Recycling of many materials is theoretically feasible through physical, chemical (remelting or recovery), feedstock recovery and other forms of closed loops. The less complex the cycle, the more resource-efficient the outcome. Using PVC as an example, many such recycling loops are already in operation in Germany (the windows industry), in the UK (bottle remanufacture), in Denmark (cable recycling), within manufacturing plants, and at pilot scale for other applications.
- Reformulation of products may be helpful, or indeed essential, to ensure that additives do not inhibit closed loops.
- Recycling should always aim to result in a material of as near to the quality of virgin product as possible. Where this is not possible, recyclate use in lower-quality products (i.e. plastic road cones or garden furniture, or wood fragments reused as chipboard) may provide an effective route to increase the number of cycles a material can make. Where possible, durable products (underground pipes, etc) should constitute the final recyclate to maximise overall longevity.
The chemical or physical properties of materials should be exploited to increase the automation of sorting of waste. Practical examples of this in operation today including magnetism in ferrous metals, detection of chlorine atoms in PVC using X-ray fluorescence, and differential centrifugation exploiting differences in the density of different types of nylon fibres.” (Stepping Stones, no. 37, 200)

In order to apply these concepts to InterfaceFLOR, the inputs and outputs of the business must be assessed.

2.3 InterfaceFLOR

2.3.1 Product

InterfaceFLOR in the UK manufactures carpet tile from petrochemicals, glass and limestone. There are two types of backing systems manufactured in the UK, the Graphlex and Glasbac systems illustrated below.

![Graphlex backing system](image.png)

*Figure 1. Illustration of Graphlex backing system (Interface Europe, Backing Systems, 2003)*
Fusion implanted textile surface

Secondary layers in thermoplastic resins

Double layer of fibre glass

Main composite in thermoplastic resins

Figure 2. Illustration of GlasBac backing system (Interface Europe, Backing Systems, 2003)

The Graphlex system is a carbon polymerised composite, incorporating layers of fibreglass. It contains, by weight, 3% fibreglass, 1-2% fleece and over 95% bitumen mix (33% pre-modified bitumen and 67% filler). The bitumen mix is applied as a melt and allowed to set on cooling.

The Glasbac system is a thermoplastic composite that again incorporates fibreglass for dimensional stability. However the primary backing constituent is based on plasticized and filled polyvinyl chloride (PVC). It is applied at ambient temperature and heated to cure.

A full description of the manufacturing process can be found in the 6 month report.

Even though the company has applied effort to ‘closing the loop’ InterfaceFLOR has not fundamentally changed the product. There is now however less material required to manufacture the product than previously. This has been an incremental change year-on-year and a gradual evolutionary process. It would be prudent to analyse how the inputs and outputs of the process have changed since the drive for sustainability began in 1994.

It is worth noting that some of the raw materials delivered to InterfaceFLOR give rise to a separate waste stream of packaging, as well as the waste produced from the actual manufacturing process. These will be considered separately.
2.3.2 Inputs

2.3.2.1 Introduction

The raw materials for carpet tile manufacturing come from a number of sources. Since we are considering material for use as filler in the PAF system, only the material that enters InterfaceFLOR will be considered; from factory gate to gate. Therefore, a summary of material inputs is shown below.

![Diagram of inputs entering InterfaceFLOR product](image)

Figure 3. Summary of inputs entering InterfaceFLOR product

This is not a conclusive description of everything that enters InterfaceFLOR, but recognises main material inputs. There are other inputs such as paper, stationery, canteen food etc, but only the industrial processes that give rise to the product are considered here for simplicity as they are produced in the greatest volumes and at greatest cost.

Each input is considered individually in order to assess the likely waste streams arising from their use. There are other sources of waste during manufacturing, but these are considered in section 2.3.3.
2.3.2.2 Primary Backing

The polyethylene terephthalate (PET) primary backing will arrive at the Craigavon manufacturing facility via road transport. There will be long rolls of material that are packaged for protection from the environment. Each roll has a central core of card which is sent back to the manufacturer for re-use. This fulfils the first of the principles suggested by the Natural Step (Stepping Stones, No. 37, 2000).

Excess plastic packaging will be sent for recycling using a simple melting process. Around 8 tonnes of polythene packaging was recycled in 2005 (Bauer, 2006). Hence there is no spare waste in the introduction of the primary backing system available for use as filler.

2.3.2.3 Yarn

Yarn will arrive for tufting to the Craigavon manufacturing site. The yarn will be packaged together on cones in cardboard boxes. The boxes are sent for recycling, along with other cardboard waste at a cost of £40/tonne. In 2005, 134 tonnes of cardboard packaging from all UK sites were recycled (Robinson, 2006).

The cones are often wound into smaller batches for design samples. This leaves a residual amount of yarn on the cones. This is often re-spun for use in further production or alternatively may be slit off of the cone. This leaves short yarn pieces that are then sold for use in blankets and bedding.

In 2005, 54 tonnes of yarn were sent for reuse in other products outside InterfaceFLOR, whilst 74 tonnes were re-blended and used for other purposes (Bauer, 2006).

The cardboard cones remaining after the material has been spun are shredded and then sold. The cardboard is of low quality as it has already been through a number of life cycles. The fibres are short and therefore the material is used only in the manufacture of egg boxes (Robinson, 2006).

The introduction of the yarn gives rise to a number of waste streams, all of which are being used currently. However, it is worth noting the smaller pieces of cardboard are readily available in large quantities.
If we consider the qualities required from the filler then the cardboard cones come close to fulfilling those properties. It is inert, readily available and will bio-degrade. The pieces of material are too large at present however and would require further processing. In addition, the cardboard is likely to absorb much of the moisture in the system, which may be detrimental. Further investigation of the cardboard is warranted.

2.3.2.4 Filler

The filler used for the backing system has historically been virgin limestone. This is being replaced with recycled filler. The material is delivered in tankers that are re-used for each delivery. In this way, the use of the filler is helping to close the loop. It will use a waste stream from another production process, whilst reusing the packaging each time.

The filler is stored, sieved and heated on-site. There are some larger particles left over from the sieving process, which are then ground and put back in to the system.

The use of the filler therefore is a good example of closing the loop, but does not provide a spare waste stream for use in PAF.

2.3.2.5 Bitumen or PVC

The bitumen is delivered via tanker and stored in large heated containers prior to use. The PVC is delivered in the same way, but it will be mixed and stored in cool plastic containers prior to use. The plastic containers are re-used on-site for each PVC batch.

At the beginning and end of each day, the processing line may be stopped. When this occurs there is some material that becomes hard and unusable. This material is removed from the processing line mechanically and may be sent to landfill. However, there is only a few kilograms of this material produced daily. Therefore it is not a viable source for filler.

2.3.2.6 Fibreglass

Fibreglass is used in conjunction with the bitumen or PVC to create the secondary backing. It will arrive on large rolls, similar to the primary backing. Some of these rolls are shown prior to processing below.
The fibreglass is delivered and stored in a similar way to the primary backing. Again there is little waste associated with this input.

### 2.3.2.7 Polypropylene Backing

This is the black roll that can be seen in the diagram above. This produces similar wastes to the primary backing.

### 2.3.2.8 Packaging

InterfaceFLOR uses cardboard packaging for its tile boxes. This uses an automated system that is both efficient and reduced manual handling.

The cardboard boxes will be tied to a pallet for delivery. The ties are manufactured from a durable thermoset that is not easily recycled and are therefore sent to landfill. However, the ties are long, difficult to handle and few in number. Therefore they are not suitable for use as filler in PAF.

The pallets are sent back to the manufacturer after use. Pallets are used throughout InterfaceFLOR to store material and product. There were 16 tonnes of pallets recycled in 2005 (Bauer, 2006).

### 2.3.3 Production

#### 2.3.3.1 Introduction

There are a number of waste streams that arise due to the manufacturing process at InterfaceFLOR. These are considered separately as they are often a mixture of materials and have more complicated disposal routes.
2.3.3.2 Pleated Paper

This has not been considered as a raw material input as it is not used in the final product. Large rolls of paper are used in the fusion bonding process. Yarn is pleated with the paper- much like a fan. It is then bonded to the primary backing system. The paper is then removed and the yarn slit. As the creases are detrimental during further processing, the pleated paper that remains may only be used once.

The material is then sent back to the manufacturers for recycling. Nearly 76 tonnes of pleated paper had to be recycled last year (Bauer, 2006).

The paper is available in large rolls and there is currently no facility for shredding or granulating such large volumes. This paper may be worthy of further investigation.

2.3.3.3 Edge and Window Waste

Rolls of material are produced by InterfaceFLOR that are then cut into carpet tiles. The cutting process can be seen in the photograph below.

![Figure 5. Photograph showing rolls of material being cut into tiles](image)

This cutting process creates waste material between the tiles cut out that is termed 'window waste'. This can be clearly seen on the photograph as a strip of material being removed from the yellow roller, shown by the red arrow. There is also waste material created at the edge of the rolls called ‘edge waste’.

This material is of the same composition as the finished carpet tile, i.e. a mix of bitumen, fibreglass, nylon, filler etc. It is difficult to reuse the material in its present form. It is also extremely difficult to separate the constituents.
Because of this, when considering closing the loop, InterfaceFLOR is investigating the reformulation of the product in line with the Natural Step guidelines. Most of this work has been in partnership with the University of York and Crystal Faraday. It is investigating the use of a ‘switcheable adhesive’ in order to separate the components of the flooring at end of life (Shuttleworth; 2006).

The material has historically been sent to landfill, although the material has gradually been reduced as efficiency procedures have come into place. This has contributed to the current figure of 900 tonnes of material sent to landfill per annum- at an ever-increasing cost (Bauer, 2006).

There has been investigation into using this waste material as filler in the current product. The material would be ground and then returned to the backing system. It is likely that this project will be undertaken in the near future and that this source of waste will be removed.

This material could be considered as filler for PAF. However, it would be a barrier to the bio-degrading of the system. This waste stream is worthy of further investigation, once the grinding process is in place.

2.3.4 Re:Entry

Although not strictly a waste product produced at InterfaceFLOR, it is worth noting what happens to the carpet tiles sold at end-of-life.

The business would take back the flooring and either re-use or recycle the material. Re-using involves cleaning the tiles thoroughly and may involve re-dyeing the surface yarn to keep in with current fashion trends. The backing may also need to be renovated in order to restore the impact resistance of the flooring. These Re:Entry products are currently donated to non-profit organisations (InterfaceFLOR, 2006).

There are however a number of carpet tiles that cannot be refurbished in this manner. This could be used in the same way as the edge or window waste.

2.4 Conclusion

It has been noted that InterfaceFLOR has been focused on reducing the waste produced by their manufacturing process. This has been highly successful and produced cost-savings. It is also obvious that waste-saving has become part of the ethos of the business and it is attempted at every level.
It is worth noting that the more waste there is in a production process, then generally the greater the cost of production. This has been shown by Interface Inc. as they claim to have avoided costs of $299 million through the process of waste elimination (Interface.sustainability.com).

'Closing the loop' has been less successful thus far, although it is obvious that reducing waste is a simpler process than redesigning product and organising take-back. However, it should be noted that there are innovative projects being undertaken that are addressing this problem, such as 'switcheable adhesives' (Shuttleworth, 2006).

The waste streams have been investigated and it can be concluded that there are some materials that are worthy of a further scoping exercise- such as the cardboard cones, pleated paper, edge and window waste. These will be assessed in the next part of the PAF investigation.

As such, there is no obvious waste-stream that is available in sufficient quantities and with the correct properties that can be used for PAF at the current time. There may be other opportunities in the future when the type of processing may change and alternative waste streams become available. Therefore it is important that waste streams continue to be monitored and assessed on a regular basis.

There are also waste streams that arise as part of other industries that may be useful as fillers. These may be investigated further as part of the PAF project.
3. The Investigation of a Resin Based on Renewable Resources

3.1 Introduction

InterfaceFLOR has committed to its ‘mission zero’ to ‘eliminate any negative impact our companies may have on the environment by the year 2020’ (Interface, 2006). As part of this, there have been incremental achievements in reducing waste, creating benign emissions, purchasing green electricity etc. This has been a gradual process of evolution rather than revolution.

In conjunction with this approach, InterfaceFLOR has been tackling innovative projects that will yield longer term results. One such project is the PAF concept, described in the 24-month report (Carter, pp 20-32, 2005). This concept introduced a resin based on renewable resources.

This resin is based on a epoxidised linseed oil (ELO) (figure 1) and cross-linker (figure 2) that will form a network as the system cures. The resulting polymer is shown in figure 3.

\[
\text{Figure 1. Simplified chemical structure of ELO}
\]

\[
\text{Figure 2. Cross-linker formed by heating dipropylene glycol in the presence of maleic anhydride}
\]
Figure 3. Cross-linker and ELO react to form polymer

With a molar ratio of diacid: ELO of 3:1, theoretically all the epoxide groups of the ELO can react with all the acid groups of the cross-linker. With a molar ratio of 1:1, in theory, all the acid groups of the cross-linker can react with just two epoxide groups of an ELO molecule, resulting in a more flexible polymer.

The initial part of the investigation involved assessing the curing time of the resin at room temperature. It was concluded that although the curing time could be reduced at room temperature using catalysts, the PAF concept was a long way from completion.

Therefore it was proposed that the resin may be used in alternative ways such as forming part of a backing system for carpet tiles or as a replacement for Interlock. These concepts are described in the 24-month report (Carter, pp 34-53, 2006) and the 30-month report (Carter, pp 12-18, 2006).

In order to decide if the resin may replace a material already in use, it must be deemed 'fit-for-purpose', i.e. it must perform as designed in service without undue failure. In the particular example of a flooring product it must perform as a stable surface, without undue risk to the user. There are other considerations that have been discussed in the 24-month report (Carter, pp 49, 2005).

Flooring is usually assessed using a large number of tests, undertaken by professional experts, approved and regularly checked to British and International Standards. These are time consuming and costly but necessary for commercial validation.
Each test is designed to simulate what may happen to the carpet in use. For example colourfastness- to light, rubbing wet and dry, fibre integrity and fibre bind for synthetic carpets.

The relationship between material characteristics and flooring performance is not yet fully understood. It is clear that harder and stronger materials are more durable in service. This is why materials such as varnished wood, ceramics, linoleum and nylon are used for flooring products, and rarely materials such as paper, foams and cotton.

While the flooring tests are useful in simulating service conditions, there is significant cost associated with the regime (Carter, p 28, 2006).

The bio-resin has a number of process parameters in manufacture that may affect the performance in service as well as the material characteristics. It is suggested that the properties determined from a sample tensile test may highlight differences in material characteristics relevant to flooring performance, without requiring a large volume of material to undergo testing.

One of the purposes of this investigation is to assess whether the tensile tests suggested as a proxy for the flooring tests are a suitable substitute.

A second part of this investigation is to assess the way in which material properties may then be affected by processing parameters such as cross-linker amount, time at elevated temperature and temperature.

3.2 Sample Preparation

The samples to be used in the tensile tests are prepared in a manner that is consistent and reproducible. The sample preparation is documented carefully. The manner in which the samples are prepared for testing is adapted from several British Standards.

A disposable compatible container is used to hold the constituents- the ELO and the diacid cross-linker. The cross-linker is first placed within a container and the mass measured using a calibrated scale- the Mettler P1200, correct to ±0.01 g. The ELO is then added to the cross-linker. As it is less viscous than the cross-linker its addition is easier to control.

The molar ratio of components required is noted and mass ratio calculated- the exact amount added is carefully controlled. It is subsequently used to calculate the exact molar ratio of components.
Any other additions that are required for the mix are added after the main components. The components are then well mixed using a magnetic stirrer at 3000 rpm for 2 minutes. This speed and time were chosen as it has previously been shown to provide an effective mix (A and F, 2005). This speed and time were also used in previous experiments in which a vegetable dye was added and visual inspection suggested that the dye was distributed evenly after 2 minutes of stirring.

The mould to be used is pre-heated in an oven to 5°C above the desired temperature. The elevated temperature is required as there is a temperature fall when the oven door is opened. The mould is removed, the liquid poured into the mould and then replaced in the oven. However, immediately upon returning the mould to the oven, the temperature is reset to the desired value with a variance of ±1 °C. This is set using a calibrated digital control.

After the required amount of time, the mould is removed from the oven and the sample is removed. It is placed on a wire rack in order to allow full air circulation at room temperature. It is then labelled in the following manner:

00.00/111/22x/AAA/Y

In this labelling system 00.00 is the molar ratio of diacid to 1 mole of ELO, 111 is the curing temperature in °C, 22x is the curing time in hours or minutes (given by x), AAA are available for other additions and Y indicates the sample letter- A, B, C etc.

There are no British Standards that describe the conditioning required for this particular system. However, there are examples within the standards for other plastics and these are used here.

The sample is then left at room temperature for 72 hours. This ensures that any resilient processes have completed in accordance with BS EN ISO 1798:1999.

The sample is then cut out using a hand press and cutter specified by BS EN ISO 1798.

The cut samples are conditioned for 24 hours to ensure that the atmospheric effects are the same with each test. A controlled atmosphere is used for traditional carpet tests of 65 ±5 % RH and 20 ± 1 °C. It therefore seems prudent to use this conditioning for the samples in each case, as well as testing in this environment.
For each set of samples, at least six samples are produced – this is to ensure that there are five samples that are suitable for testing, as specified in BS 2846-2:1981 ISO 2602-1980. The samples are individually labelled in the same manner as before and are then ready for testing.

There were a range of samples manufactured for tensile testing, designed to show material variation with processing. The temperature of 150 °C and time of 30 minutes had been suggested from previous work (A and F, 2005) as the most effective for cure of the material.

180 °C was also chosen as this was the temperature at which a backing system is cured in InterfaceFLOR. Part of the test was to determine if the material could be cured at a much shorter time than the 30 minutes predicted.

A number of samples were manufactured with differing

- Molar ratio of components and cured at 150 °C for 30 minutes
- Cure times at a 2.5:1 molar ratio and cured at 180 °C
- Cure temperatures at a 2.5:1 molar ratio and cured for 30 minutes

3.3 Testing Regime

3.3.1 Tensile Tests


"This British Standard describes the determination of tensile properties of plastics, including general principles. The methods described in this standard are used to investigate the tensile behaviour of the test specimens and for determining the tensile strength, tensile modulus and other aspects of the tensile stress/strain relationship under the conditions defined."

After cleaning off any loose particles, the central portion of the dumbbell is measured across the width and thickness to ± 0.1 mm. Three measurements are taken and the arithmetic mean value for the width and thickness calculated. Five samples are measured in turn and the results logged.

The gauge length is marked on the samples, approximately equidistant from the mid-point, not more than 50 mm ± 1mm apart (EN ISO 1798:1999).
The test specimen is then clamped in the Testometric Micro 350 (figure 4), calibrated by UKAS to ISO 5893 and BS EN ISO 7500-1:1999 to grade 0.5, taking care to align the longitudinal axis of the test specimen with the axis of the testing machine and to set the gauge length correctly.

Figure 4. Testometric Micro 350

The stiffness of the machine has been calculated by the manufacturers and is accounted for in the electronic calculation of the distance moved by the crosshead.

The test specimen is extended along its major longitudinal axis at a constant speed of 100 mm/min until the specimen fractures. Any fractures that occur outside the gauge length, within 10 mm of the jaws or where there is an obvious defect are discarded.

A correctly fractured specimen is shown below in figure 5.

Figure 5. Fractured specimen
The maximum force and elongation is measured electronically using the Testometric Micro 350 and a stress-strain graph is produced, much like the diagram below.

\[ \text{Limit of linear elasticity} \]
\[ \text{Plastic range} \]
\[ \text{Gradient} = E \]

\[ \sigma \]
\[ \varepsilon \]

*Figure 6. Schematic stress-strain curve*

From the graph, the properties of $\sigma_y$ (yield stress) and $\varepsilon_{\text{max}}$ (maximum strain) can then be determined. The Young’s modulus of elasticity is calculated from the stress at a strain of 0.0005 and the stress at a strain of 0.0025 (i.e. a secant modulus between 0.05 and 0.25% strain). This is given in BS EN ISO 527-1:1996.

These calculations can be completed for each of the samples and the arithmetic mean and standard deviation can be found. These results are then tabulated.

### 3.3.2 Flooring Tests

Flooring can be tested using a variety of methods to assess if it is 'fit-for-purpose'. These tests are designed to ensure that the customer receives a product that is suitable for their needs- often specified through the use of a grading system. The grading system for the carpet industry will assign a number which designates the level of use that a carpet can undertake in practice- from heavy contract to light domestic use.

Certain tests, such as those that were described in the 12-month report (Carter, pp 31-33, 2004), rely on the expert judgment of professionally trained assessors through visual assessment. One such test is the Vetterman drum test.
British Standard BS ISO 10361:2000 describes the Vetterman drum and hexapod tumbler tests. They both work on the same principle of simulating the conditions of use. The Vetterman drum is a large apparatus that revolves with a steel ball inside. This ball has rubber feet, designed to fatigue the flooring which is lining the inside of the drum. A circular brush constantly removes broken fibres. The apparatus is shown below.

![Diagram of Vetterman drum test](image)

**Figure 7. Diagram of Vetterman drum test**

![Photograph of Vetterman drum test](image)

**Figure 8. Photograph of Vetterman drum test**

The flooring will then be assessed for changes in appearance and graded.
The resistance to the application of a static load is important in the flooring industry. In the lifetime of a flooring product there are often a number of heavy pieces of furniture that will provide a consistent heavy load.

BS 4939:1987, ISO 3416-1986 describes a method of testing designed to measure this effect. A known pressure is applied to the sample of flooring, through the use of a heavy load and circular foot for 1 hour. The resulting loss of thickness is measured and recorded. The load is then re-applied for a further 23 hours. After the load has been removed, the appearance is again assessed.

Electrical resistivity of a sample is measured using the methods described in BS 6654:1985. This involves the application of an electrode to a sample placed on a metal plate. A 550 V load is applied to the sample and the conductivity measured. Since electrical resistance is the inverse of conductivity it can be determined.

3.4 Results

3.4.1 Tensile Tests

In each of the graphs shown below, the average of at least five tensile tests is shown. There is one standard deviation of the results also shown on the graphs.

Molar ratios were changed and samples cured at 150 °C for 30 minutes. The results of the tensile tests are shown below with trendlines:
Figure 9. Mechanical properties measured as a result of tensile tests on material cured at 150 °C for 30 minutes

Samples were manufacture with a 2.5:1 molar ratio (diacid:ELO) and cured for differing times at 180 °C. The mechanical properties determined from the tensile tests on these samples are shown below. Trendlines have been added.
Figure 10. Mechanical properties measured as a result of tensile tests on material with a 2.5:1 molar ratio (diacid:ELO) cured at 180 °C

Samples were also manufactured at the 2.5:1 ratio and cured for 30 minutes at three different temperatures. The results of the tensile tests are shown in figure 11, also shown with trendlines.
Figure 11. Mechanical properties measured as a result of tensile tests on material with a 2.5:1 molar ratio (diacid:ELO) cured for 30 minutes

The samples that were tested using the traditional flooring tests were also subjected to tensile tests. The results are shown in figure 12.
Figure 12. Mechanical properties measured as a result of tensile tests on material also tested using traditional flooring tests

3.4.2 Flooring Tests

The results of the static loading, Vetterman drum and electrical resistance tests are tabulated below. They are shown against the test results for an Interlock tile.
### Table 1. Results of flooring tests

<table>
<thead>
<tr>
<th>Test Type</th>
<th>Measured Quality</th>
<th>02.00/150/30m/000</th>
<th>01.00/150/30m/000</th>
<th>Interlock</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass g per m²</td>
<td></td>
<td>10300</td>
<td>10000</td>
<td>7400</td>
</tr>
<tr>
<td>Thickness mm</td>
<td></td>
<td>9.9</td>
<td>10</td>
<td>6.9</td>
</tr>
<tr>
<td>Static loading</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Compressibility (mm)</td>
<td></td>
<td>0.2</td>
<td>0.5</td>
<td>0.4</td>
</tr>
<tr>
<td>Depth of marks after 1 hr (mm)</td>
<td></td>
<td>0</td>
<td>0</td>
<td>0.1</td>
</tr>
<tr>
<td>Visibility of marks</td>
<td></td>
<td>5</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Vetterman Drum (5000 revolutions)</td>
<td></td>
<td>5</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Structure</td>
<td></td>
<td>5</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Shade</td>
<td></td>
<td>5</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Overall change of appearance</td>
<td></td>
<td>5</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Final rating</td>
<td></td>
<td>5</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Vetterman Drum (22,000 revolutions)</td>
<td></td>
<td>4.5</td>
<td>3</td>
<td>5</td>
</tr>
<tr>
<td>Structure</td>
<td></td>
<td>4.5</td>
<td>3</td>
<td>5</td>
</tr>
<tr>
<td>Shade</td>
<td></td>
<td>4.5</td>
<td>3</td>
<td>5</td>
</tr>
<tr>
<td>Overall change of appearance</td>
<td></td>
<td>4.5</td>
<td>3</td>
<td>5</td>
</tr>
<tr>
<td>Final rating</td>
<td></td>
<td>4.5</td>
<td>3</td>
<td>5</td>
</tr>
<tr>
<td>Electrical Resistance</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Horizontal (MΩ)</td>
<td>&gt;50</td>
<td>&gt;50</td>
<td>20</td>
<td></td>
</tr>
<tr>
<td>Vertical (MΩ)</td>
<td>&gt;50</td>
<td>&gt;50</td>
<td>20</td>
<td></td>
</tr>
</tbody>
</table>

### 3.5 Discussion

#### 3.5.1 Altering Molar Ratio

It can clearly be seen from figure 7 that changing the molar ratio of components has some effect on Young’s Modulus, strain to failure and peak stress.

Theoretically at a molar ratio of 3:1 all the reactive groups have combined to create the strongest polymer. This is because the greater the number of cross-links, the stronger the polymer will be. There are more bonds to hold the structure together that need to be broken in order to destroy it.

However, it can be seen that the nominal peak stress tends to increase and then decrease with a peak at a ratio of diacid: ELO of approximately 2:1. There is a similar trend observed for the Young’s Modulus with a peak occurring at a ratio of approximately 2:1 followed by a sharp fall.
This peak can be explained if we consider the mobility of the components. In order for the reactive groups to combine, they must first meet. If the reaction occurs, then a solid polymer begins to form. As more polymer forms, the viscosity of the system increases. As the viscosity increases, the mobility of the components decreases and therefore there is less likelihood that the reactive groups can meet and combine further.

At 150 °C for 30 minutes there will be a finite amount of energy available to the system. The more diacid there is available for cross-linking, the greater the likelihood that an individual reaction will occur and the greater the amount of cross-linking. If there are more cross-links in one system than another, it will have a greater Young’s Modulus and peak stress. This is because there is more force required to stretch and break these bonds.

However, there comes a finite point beyond which the mobility of the reactants is restricted and no further reactions can occur. Beyond this point, there will be excess diacid in the system. It is theorised that this will then act as a plasticizer and fill the gaps left by the cross-linking process. This is shown by the decrease in Young’s Modulus and peak stress beyond the 2:1 ratio.

It can also be seen that the strain to failure increases dramatically and then increases at a lesser rate as the molar ratio increases. It is theorised that the strain would increase in line with the Young’s Modulus and peak stress as the number of cross-links increases. However, beyond the 2:1 ratio it is theorised that the number of bonds does not increase.

If the excess diacid does act as a plasticizer, then this would explain the continued increase in strain to failure. The bonded polymer can continue to stretch around the plasticizer as it also deforms upon the application of a force.

### 3.5.2 Altering Cure Time

Figure 10 shows that at 180 °C increasing the cure time has a dramatic effect on Young’s Modulus. However, there is much less effect seen on the peak stress and strain to failure.

The two components are mobile in the liquid form and must meet to for the reactive groups to combine. When this occurs, a solid polymer is formed. This causes the liquid to be more viscous and therefore the remainder of the reactive groups are less mobile as reaction time continues.
It was observed that the material was solid after 5 minutes conditioning at 180 °C. Beyond these five minutes it is theorised that the reactants are not sufficiently mobile to create any new cross-links between independent molecules.

However, energy is continuously added to the system. This energy cannot be used for mobility and may be used by the system in other ways, such as increasing the number of cross-links with neighbouring molecules and therefore increasing the stress required to fracture this system.

The peak stress continues to increase gradually with time, whereas strain to failure remains relatively stable. It is theorised that this is because the strain will not increase any further with additional cross-linking.

It has already been shown that the peak stress and Young's Modulus at 150 °C for 30 minutes occurs at a 2:1 ratio. Therefore it is theorised that there is excess diacid in this system. With the energy input this excess may react further with the ELO, although there is a lack of mobility restricting these reactions.

There is a plateau in the Young's Modulus that occurs after 20 minutes. It may be that beyond this time there are no further reactions that can occur as neighbouring molecules have reacted as fully as they are able. Therefore the stiffness will not increase further.

3.5.3 Altering Cure Temperature

Figure 11 shows the effect of altering cure temperature on mechanical properties. It can be seen from this graph that there is little change in peak stress with an increase in temperature. There is also little change in the strain to failure. However, Young's Modulus falls slightly with an increase in temperature.

It was shown by the previous experiments that at 180 °C the system had become solid. Therefore it is theorised that at these cure temperatures the systems would also have been cured at times much less than 30 minutes. Therefore the mobile reactants have created the finite amount of cross-links available to the molecules.

However, at greater temperatures, with excess diacid, it is theorised that there are a greater number of reactions that become available. If a greater number of reactions are possible, then the material will become more viscous more quickly and the mobility will be lost.

The excess diacid may also react with individual ELO molecules, creating shorter chain molecules and a less stiff structure. This would explain the slight drop in Young's Modulus, with little effect on the peak stress.
3.5.4 Flooring Tests

The results from the flooring tests shown in table 1 can be compared with the tensile test results shown in figure 12. The tests show the comparison between two resins cured at 150 °C for 30 minutes with different molar ratios (2:1 and 1:1) and Interlock- an InterfaceFLOR product.

It can clearly be seen that Interlock has a much higher Young's Modulus, peak stress and strain to failure than the resin samples. The 2:1 molar ratio also has appreciably higher properties than the 1:1 molar ratio.

It was therefore expected that the Interlock sample would perform significantly better in the flooring tests than the resin sample.

However, it can be seen from table 1 that both the 2:1 molar ratio and Interlock perform well, achieving a level 5 (the top score) in a number of categories. All samples performed well in the static loading test, with the 1:1 molar ratio suffering the greatest indent of 0.5 mm.

The 1:1 molar ratio achieved a 3 grading on the Vetterman drum test, in comparison to the 5 achieved by the Interlock sample and the 4.5 achieved by the 2:1 molar ratio.

Given that the mechanical properties were so dissimilar, it is unexpected that the 2:1 molar ratio and Interlock would perform so similarly. However, in the example of these tests it can be seen that the 2:1 molar ratio is 'fit-for-purpose' and would be passed as a level 4.5. Therefore it may be surmised that the Interlock sample was over-designed.

3.6 Conclusion

It has been seen that changing the molar ratio of components does affect the mechanical properties of the resin. Strain increases with increasing molar ratio, whereas the Young's Modulus and peak strain peak at the 2:1 molar ratio (diacid:ELO).

From the discussion of results it may be concluded that plasticizers could be of use in this system to increase the strain to failure.

It has also been shown that increasing cure time will have a dramatic effect on Young's Modulus, but less so on peak stress and strain to failure. This may be because of the cross-linking mechanisms that are available for this reaction.
It can be concluded that the resin cures at elevated temperature in a much shorter
time than the 30 minutes originally predicted. This may be of value when
considering other processing routes for this system.

Altering the cure temperature during a 30 minute cure time has little effect on the
mechanical properties. However, it is possible that the material cures in a much
faster time. This is certainly worthy of further investigation.

It is still debatable whether a greater Young’s Modulus, peak stress or strain to
failure would be more beneficial for a flooring product. It is anticipated that a
combination of both would be preferable and this has been shown by the
preliminary flooring tests.

It is recommended that during next stage of this investigation samples are used in
flooring trials, i.e. they are placed as a flooring product in-situ. This would lend
some credence to the flooring tests. It would also be prudent to trial a range of
samples and compare these results to the mechanical testing to further vindicate the
choice of these tests.
3. **Further Work**

The remainder of this project time will be spent compiling the results from this investigation and assembling them together in a structured thesis document.

The floor trials of the ELO system will be complete in May 2007. The results will then be documented and discussed to be included in the thesis.

Light fastness tests will be conducted on some of the material used in the floor trials, both with and without recycled filler. This will be concluded by the end of April 2007.

As an addition to this project, a series of presentations is also being conducted to key stakeholders in this project. This is supported by a series of informative guides to the presentations which are distributed before the event. The aim of these presentations is to obtain constructive feedback and seek a determined route for this project at the end of the period.
Figure 1. Gantt Chart for next 12-month period
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Dianne Carter

42-Month Report

01.10.06 - 01.04.07

“Towards Sustainable Design and Manufacture of Textile Flooring Products”
Abstract

The EngD project is looking at more sustainable flooring solutions within the context of InterfaceFLOR’s goal to be a sustainable company by 2020.

Success has been in introducing renewable content into the current textile-flooring product. In a previous report (Carter, 2004), the introduction of recycled filler into the tile backing has shown that the Graphlex backing system can incorporate recycled material up to 67 wt%.

A resin system has been introduced based on epoxidised linseed oil (ELO). The investigation of the ELO system is described in the appendix to this report. The scoping exercise which involved altering processing parameters and recording change in material properties is described. The material has also undergone flooring tests, described in the paper, and the results are compared to those from the mechanical tests. An edited version of this paper will be submitted to the Journal of Industrial Crops and Processes in April 2007.

Samples of the ELO system have undergone standard flooring industry tests which have been described in the 36-month report. Further validation of these tests is being undertaken through the use of flooring trials, described in this report.

The further work section describes in detail the work to be undertaken in the next 6 months of this project. This section also includes a Gantt chart.
1 Introduction

1.1 Objectives of the Project in the Current Reporting Period

The EngD project has led to the investigation of a resin system based on epoxidised linseed oil (ELO). This preliminary investigation of this system has been described in the 36-month report.

The report described the results from factorial variation of molar ratio, cure temperature and cure time. These experiments were designed to show the effect of changing one processing parameter, whilst all others remained constant.

The 36-month report also described the results of flooring tests on two samples that were compared to a 100% PVC product manufactured by InterfaceFLOR. The results from the tensile tests and the flooring tests were then compared.

Planned work for the six month period from month 36 to 42 would be focussed on conducting further flooring trials. The purpose of these trials was to compare the predicted results from the standard industry tests with in-situ testing which is often conducted in the flooring industry.

1.2 Report on Progress since Month 36

The results from the work conducted up to the 36-month report on the ELO system are described in Appendix A. This includes a description of the tensile tests conducted on the material and indicative tests used in the flooring industry for comparison. An edited version of this report is due for submission to the Journal of Industrial Crops and Processes in April 2007.

The flooring trials are described in Chapter 2. Samples are secured in a high-traffic environment and documented on a monthly basis. These trials commenced in November 2006 and are due for completion in May 2007.

Chapter 2 also includes a description of the inspection method used on these samples on a monthly basis. This includes visual inspection and a description of colour measurement.

Chapter 3 describes the remaining experimental work to be conducted for this project as well as the reporting to be completed.
2. Flooring Trials

2.1 Introduction

When new flooring products are constructed, i.e. with new yarn constructions, backing systems or surface material, they are comprehensively tested to ensure that they meet industry quality standards. This will involve completing the full regime of flooring tests that have been described in previous reports (Carter, 2005, Carter, 2006). The flooring product will also be subjected to in-situ testing in a high traffic area in order to verify the performance predicted in practice by the flooring tests. An area of floor used to assess these flooring trials at InterfaceFLOR is shown in the photograph below. Here many different types of carpet tile are placed together, tested and assessed.

Figure 1. Flooring trial area
Any other new flooring, such as the ELO resin system, will have to undergo similar testing procedures. The ELO samples were manufactured and needed to be secured in place, surrounded by a material of similar height and characteristics such as vinyl and linoleum in order to minimise health and safety risk. The samples were cut using a standard press and a relief cut from samples of linoleum. Linoleum of similar thickness to the ELO system was chosen. Both the ELO samples and the linoleum were secured using the same adhesive.

It was important during the testing period that some measure could be made of the performance of the material. There were several potential methods explored. For example, samples could be lifted and their mass and thickness measured after a set period of time. However, it would not be practical to remove the samples because the removal would likely damage both the sample and the adhesive.

The dimensions of the samples were documented thoroughly before the trial began. The mass of the samples along with the average width was measured; this is described in section 2.1. The flooring tests performed on the samples indicated that a large amount of mass and/or thickness was not lost during the testing cycle. There is a possibility these measurements of mass and thickness lost may be redundant, but it is important that they are recorded to verify this. The sample dimensions will also be documented after the trials are complete for comparison purposes.

Methods of non-pertubative, in-situ measurement were then considered. A visual inspection recorded with photography on a monthly basis, was undertaken. This is described in more detail in section 2.3.

In addition to visual assessment, the colour of the samples was measured. It was predicted that the colour of the samples would vary with time as there may be damage to the material and colour change as the material ages. The sample colour is homogeneous throughout the thickness and therefore removing material should not affect the colour. The samples are subjected to continuous foot-traffic and cleaning cycles on a daily basis. The large particles of loose soil could be picked up by the vacuuming process, although some smaller soil particles could remain. This would change the colour of the samples, in the same way as carpet retains soil over time. The purpose of the colour measurement, described in section 2.4, is to detect this difference. This would also be verified by visual assessment. Signs of soil include darkening or lightening of areas of the samples and prints resulting from traffic.
2.2 Method

During the manufacturing process of the ELO system, one surface of the sample was in contact with the metal container used to hold the sample, whilst the other surface was exposed to the air. When recycled filler was used in the samples, to provide bulk at low cost, there was invariably a small amount of air incorporated into the samples. Despite efforts to minimise this through careful mixing, some air remained. As they were viscous, despite the addition of heat during the curing cycle which would normally reduce the viscosity of the system, there were some air bubbles that remained. They could evaporate at the surface, but they remained at the surface in contact with the metal container, observed through visual inspection. Therefore the two surfaces were compared separately.

The samples were glued to the floor with an adhesive and will be removed at the end of the testing period. They were cut using a standard press and set in a linoleum surround. Linoleum has been used as a surround as it is of similar thickness to the ELO system and readily available. The sample size was also chosen to have a diameter of 140 mm as this would be large enough to exhibit visual signs of differences in performance as well as provide a large enough size for colour measurement.

The samples were placed in the same high traffic environment as other flooring products under test. The completed area is shown below.
Figure 2. Trial area of ELO system samples, with PVC samples shown to the right

PVC samples are also included in this trial as comparison samples. They were used as a standard in the flooring tests and the tensile tests and therefore it is appropriate to use them again as a standard.

The samples are then assessed on a monthly basis. As previously stated, photography is one method that is used to capture change in visual appearance of the samples and this is described below.

2.3 Photography

2.3.1 Introduction

Photography is a useful tool in visual assessment. This ensures that a consistent record can be kept of any visual assessment made. It is normal practice in the carpet industry to grade samples using visual assessment. For this project it is also useful to have some measure of those visual assessments and therefore photography is used.
2.3.2 Method

On a monthly basis, at the same time as the colour measurements are taken, described in section 2.4, photographs of the samples are taken. Each sample is photographed individually using a Kodak EasyShare DX 7630 and a Schneider-Kreuznach lense in close-up mode. Each picture is recorded using 6 megapixels. The photographs are taken at an angle of approximately 70° to the horizontal, in order to reduce the specular reflection from ambient lighting on the sample, which may in turn mask imperfection on the surface.

An example of a picture taken using this method is shown in figure 3.

![Sample used in flooring trial](image)

Figure 3. Sample used in flooring trial

2.3.3 Results

Results are ongoing and during the first part of this trial, in comparison to the PVC and linoleum samples, the ELO system samples visually appear to be performing well.

As well as photography, another method of assessing the samples is being undertaken. This is the measurement of the colour change which may indicate accumulation of soil or further curing with time.
2.4 Colour Measurement

2.4.1 Theory

Colours can be measured in a variety of ways and have several different components to their appearance. Colours can be light or dark as well as appear brighter or duller. This is not simply a measure of the amount of black or white added to them, it is a factor of other considerations as well.

Humans perceive colour as light is reflected from a surface or transmitted from a source, absorbed by the rods and cones in the eye and converted via the optical nerve to the brain. Some of the light waves are absorbed by the object and it is this reduction and removal of light waves that gives an object its colour. It is also a reflection of the wave range of light that has been shone on the sample.

The human perception of colour is highly subjective. Eye fatigue, age and other physiological factors can influence colour perception. A person’s description of a colour is also highly individualistic as it will depend on their personal preferences and references. Therefore it is important to have a subjective measure of colour, not subject to human error.

The hue is described as how a person will perceive an objects colour, e.g. red, orange, green etc. The colour wheel below shows the continuum of colour from one hue to the next. The second disc shows the difference when chroma is introduced- often described as the vividness or dullness of a colour. Colours in the centre are grey, whilst those at the edge are more vivid.

![Figure 4. Disc showing hue and disc showing chromaticity (X-Rite, 2004)](image)
Colour is considered to be a three-dimensional measurement. If the lightness and darkness are ignored, the colour can be plotted on a two-dimensional graph with two axes, a* and b*. This is shown in the figure below.

Figure 5. The CIELAB colour chart (X-Rite, 2004)

The a* axis runs from left to right. A colour movement in the +a direction depicts a shift toward red, one in the −a direction a shift towards green. Along the b* axis, +b movement represents a shift toward yellow and a −b movement toward blue. Therefore a colour with a high a* value and a negative b* value will appear purple.

If the third dimension is reintroduced and this disc is part of a sphere, the light and darkness of a colour can be considered. This is shown by figure 6, below.
Figure 6. The $L^*$ value is represented on the centre axis. The $a^*$ and $b^*$ axes appear on the horizontal plane (X-Rite, 2004)

The centre $L^*$ axis shows $L = 0$ (black or total absorption) at the bottom. At the centre of this plane is neutral or grey. Therefore, a colour that has a negative $a^*$ value and a zero $b^*$ value, with a high $L^*$ value will appear as a very light green.

Since colour can be described in this way, then a method of measuring these aspects is required. There are a number of instrumental methods of measuring colour to $L^*$, $a^*$ and $b^*$ co-ordinates, many of which use the application and reflection of a beam of light. The method shown below was chosen as it was simple to apply in-situ and would give accurate details instantaneously. The method chosen and the means of operation are shown in section 2.4.3 below.

2.4.3 Method

At InterfaceFLOR, A Chroma Meter CR-210 was available as it is used to measure colour changes of production samples from trial samples. This was used to assess the colour of the samples.

"A pulsed xenon arc lamp is applied through a mixing chamber that produces a diffuse, even illumination across the surface of the sample. Only the light reflected perpendicular to the surface is collected by the optical-fibre cable for color analysis" (Minolta, 1998). The equipment used is shown in the diagram below.
A double-beam feedback mechanism measures both incident and reflected light through the use of six high-sensitivity silicon photocells.

The illumination is applied over a 50 mm diameter circular area with a 0° viewing angle. This wide diameter is particularly useful for measuring surfaces that contain a variety of colours since spot colour is then averaged. The results are then averaged and values for L*, a* and b* are calculated.

"The use of diffuse illumination and a large measuring area results in a reading that is affected by the amount of specular reflection present" (Minolta, 1998). There are mechanisms in place to compensate for this, although very glossy surfaces cannot be reliably measured. The Chromo Meter is regularly calibrated using a calibration plate before use. It can be seen visually from the photograph below that this calibration plate has an equally reflective surface as the most glossy sample. Therefore the effect of gloss may be discounted.
Figure 8. Calibration plate and sample

Since the colour is already averaged over the surface, it is not necessary to undertake a number of measurements for each sample. However, a scouting trial was conducted whereby the same sample was repeatedly measured using this method. This showed that there was high consistency with results. Since the samples are larger than the 50 mm diameter measuring head, for the purpose of this trial, three different areas are measured and the mean calculated.

2.4.4 Results

The samples were fixed in the trial area and measured on a monthly basis. The results are ongoing and will be published in the final report. Early results show that there is some change in colour measured over time.

2.5 Discussion

The samples used in the flooring system appear to be performing well in a high-traffic environment. However, they are exhibiting signs of soil. After the final set of measurements, the samples will be thoroughly cleaned and compared to results before cleaning. This will give some indication of the effect of soil.

It may also be useful to consider the effect of light bleaching on the samples. Therefore some samples will be subjected to a light fastness test, again for comparison purposes.
3. Further Work

The flooring trials of the epoxidised linseed oil (ELO) system are ongoing and in-situ assessments will be completed in May 2007. The samples will then be evaluated post-instillation. The samples will be removed from the floor and an attempt made to remove any excess soil and adhesive. The evaluation will involve measuring the sample dimensions, measuring weight, visual assessment and final colour measurement.

The effect of ultra-violet light on samples of the ELO system will be assessed via the use of industry standard light-fastness tests. A common test used in the textile industry is the Xenon fading lamp test, described in BS 1006:1990. Specimens are cut to 70 mm x 120 mm and mounted in small specimen holders. A 1,500W air-cooled xenon arc lamp is placed in a chamber.

"Slot-in specimen holders are mounted on a revolving rack and at a given distance in circular fashion around the vertical lamp unit. The rack rotates at 5 min⁻¹. After each revolution of the rack, the sample holders are turned 180° about their longitudinal axis. The surface area of specimen radiated at any one time is 450 cm² in the case of the test apparatus with a 1 500 W xenon arc lamp and 1 800 cm² with a 4 500 W xenon arc lamp." (BS 1006:1990)

The specimens will be removed at the end of the testing period and inspected. This will be completed by the end of May 2007.

Stain resistance of the samples will also be assessed using a standard test procedure used in the carpet industry. Staining of floor coverings by spilt beverages is a common problem and it is likely that the spillage may not be cleaned immediately. An assessment of staining by some common beverages will be made using in-house tests developed for textile and other floor coverings.

Staining solutions of 25 g/litre of coffee and a proprietary blackcurrant juice, containing food colorant dyes are used. These were chosen as they have been shown to provide the most staining since the coffee has disperse dye characteristics, whilst the blackcurrant juice has acid dye characteristics. The two spots of each are placed on either side of the sample, as shown in the figure below. They are then left to dry at room temperature for 48 hours.
Hot water extraction used

Coffee

Blackcurrant juice

Stains left for comparison

Figure 1. Schematic of stains applied to sample

After this time half the samples are cleaned using running distilled water until the water runs clear. The two stains were then compared using a grey-scale and graded by fully trained assessors from 1-5, where 5 is best performing. This stain resistance test will be conducted in April 2007.

As an addition to this project, a series of presentations is also being conducted to key stakeholders at InterfaceFLOR. This is supported by a series of informative guides to the presentations which are distributed before the event. The aim of these presentations is to obtain constructive feedback and seek a determined route for this project at the end of the period.

The remainder of this project time will be spent compiling the results from this investigation and assembling them together in a structured thesis document before 15th September 2007.

A Gantt chart describing the next six months is shown overleaf.
<table>
<thead>
<tr>
<th>Activity</th>
<th>Jan</th>
<th>Feb</th>
<th>Mar</th>
<th>Apr</th>
<th>May</th>
<th>Jun</th>
<th>Jul</th>
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<th>Sep</th>
<th>Oct</th>
<th>Nov</th>
<th>Dec</th>
</tr>
</thead>
<tbody>
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<td>Manufacture Test Samples</td>
<td></td>
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Figure 2. Gantt chart showing final six months progress
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Appendix A

An Investigation of Epoxidised Linseed Oil as an Alternative to PVC in Flooring Applications

D. Carter¹, N. Stansfield¹, R. Mantle¹, C. France² and P. Smith²

1. InterfaceFLOR, Shelf Mills, Halifax, UK. HX3 7LT
2. School of Engineering, University of Surrey, Guildford, Surrey, UK. GU2 7XH

Abstract

This paper considers the sustainability issues regarding some of the materials used in flooring applications. A number of the products used contain a large amount of embodied energy and have issues with reuse, recycling and disposal. It is argued that epoxidised linseed oil, made from renewable resources, could provide an attractive alternative to PVC flooring products in some situations. The objective of this study is to assess the effect of processing parameters on the final cure product of epoxidised linseed oil and a di-acid cross-linker. The final cure product is assessed for performance through a variety of methods and compared to other flooring materials. This paper shows that for contract use, the product may have comparable performance to PVC products.

1. Introduction

The flooring industry has been low profile historically, spending little on advertising, until recently when this increased from £15 million in 2001 to more than £38 million in 2006. The burgeoning housing market coupled with the influence of home makeover shows has led to the growth in the home flooring industry which is now worth £2,030 million (Mintel, 2006).

The smooth flooring industry now makes up a significant portion of the home flooring market with a 35 % market share by value in 2006. It has continued to expand in recent years with a 163 % rise in sales between 1999 and 2004 and it was estimated that over £720 million would be sold into homes in 2006. Wood and laminates dominate this smooth flooring market with a 65 % market share and vinyl is next with 27 % by square metres sold (Mintel, 2006) - the remaining 8 % market share is divided between ceramic tile, linoleum, cork and stone.
There has been increasing external pressure on the manufacturing supply chain of the flooring industry to demonstrate greater sustainability, e.g. through the use of renewable resources, reducing embodied energy, reusing, recycling and using the most appropriate method of disposal at end of life. Poly-vinyl-chloride (PVC) is used extensively in the flooring industry at the present time, as a top surface in vinyl, as a backing material and as a stand-alone product. PVC has also been problematic with claims to links of cancer and poor routes of disposal (CEC, 2000, Ohlson and Hardell, 2000, Forest et al, 1995).

The vinyl industry has attempted to address this challenge through reducing the energy required to manufacture, the water usage and the waste created during the manufacturing process (The Vinyl Institute, 2007). However, there remains a large amount of embodied energy in the finished product and it is difficult to reuse, recycle or dispose of without damaging the environment further. The resilience of vinyl can lead to long lifetimes in comparison to other materials and can make them an attractive product.

As indicated already, linoleum, which is often confused with vinyl, makes up currently a very small proportion of the market for smooth floor coverings. Linoleum has been manufactured from linseed oil, which is attractive as it is a renewable resource. Linseed oil is produced from the flax plant, which yields oil and linen. Around 1 million tonnes of oil is produced annually, with 60,000 tonnes used in the EU- of which 15,000 are used in the technical and chemical industries (Spencer, 2002). The oil has been used as a paint binder, wood finisher and in the production of linoleum. The oxidation of linseed oil through exposure to atmospheric conditions and the application of heat allow it to form a leathery skin, which, combined with the fillers and other reagents gives linoleum its hard-wearing properties (Simpson, 1997). Linoleum has been found to be a more 'environmentally favourable' option to other flooring such as vinyl and 100% PVC products (Johnsson et al, 1997, Potting and Blok, 1995).

Although the production process for linoleum has been optimised, it has not been extensively modified in the last 150 years and the manufacturing process is constrained to large rolls, which in turn require complex instillation procedures. The time taken for linoleum to season is around two to four weeks in drying rooms. This time would be considered excessive for any other flooring industry, such as the carpet industry, which, while seeking material to replace PVC in the carpet backing, requires a finished product to be delivered in days. This has contributed to linoleum becoming more of a niche product as sales have declined. Manufacturing time could potentially be reduced through the epoxidation of the linseed oil, which may also provide comparable performance to PVC products.
Epoxidised linseed oil (ELO) can be formed from the linseed oil during commercial processes. There may be concerns that this process consumes a large amount of energy. While this energy is not negligible, it is in fact comparable to the energy consumed through the use of fertilisers during the flax crop-growing phase (Bartmann et al, 2000). ELO has been shown also to be environmentally preferable to petrochemicals in other applications (Diehlmann et al, 2000) and therefore it may be considered that it would be environmentally preferable to PVC.

The purpose of this work is to investigate the reaction of ELO with a known diacid, without the presence of a catalyst, in order to form a cured system that could be capable of substituting for linoleum or part of the carpet-manufacturing process.

In section 2 of this paper the materials used are described. The ELO is a long-chained acid and therefore a cross-linker was required to bind with the liquid ELO to produce a solid material. The two components are detailed separately.

Section 3 describes the process of manufacturing the samples. This process had to be controlled carefully in order to ensure both accuracy and replication of large-scale manufacturing processes. A number of samples were manufactured by replicating some of the processing conditions for PVC in a plant that manufactures backing material for carpet.

Section 4 describes the tests that were used to assess performance. Initially a large range of materials were investigated and characterised using tensile tests. The range of material variables comprised change in molar ratio of components, cure time and temperature. This scoping exercise established a ‘best and worst-in-class’ for the ELO system, without the need to undertake a large number of flooring tests, since these tests require a large area of material (> 1 m²) for each specimen.

The two chosen materials were then tested using the industry standard tests for flooring and the results compared to those obtained from a PVC tile. These tests showed that the new material could indeed replace the PVC in some performance applications.
2. Materials and Methods

2.1 Epoxidised Linseed Oil (ELO)

ELO is available commercially from a number of outlets and was obtained as Lankroflex L from PolyOne Polymer Coating Systems. The fatty acid composition of linseed oil is dominated by C18 fatty acids, C18:2 (16% of oil) C18:3 (50% of oil) (Turner, 1987). The main fatty acid, linolenic acid (C18:3) contains three carbon-carbon double bonds (Boquillon and Fringant, 2000). These are the bonds that are oxidised in the production of linoleum. However, these bonds can also be epoxidised to form a highly reactive chemical that can be readily cured with different anhydrides in the presence of a catalyst.

An epoxide is a cyclic ether with only three ring atoms. The ring is approximately an equilateral triangle with highly strained bonds at 60° to each other. The strained ring makes epoxides highly reactive and susceptible to nucleophilic addition via the use of an acid or base. The ELO is composed mainly of epoxidised linolenic acid. The chemical structure is shown in figure 1.

![Figure 1. Schematic of epoxidised linseed oil](image)

2.2 Cross-linker

The ELO requires a cross-linker in order to create a solid structure. The cross-linker was selected in accordance with a number of criteria. The primary requirement was that the entire system had initially to be liquid at room temperature and therefore suitable for use in the current manufacturing process used for backing carpet with PVC and producing vinyl flooring. This pre-requisite was addressed during the course of a preliminary investigation into the system (Koelewijn et al, 2005).

The cross-linker is produced currently from non-renewable resources. There is no rationalisation for this and much of the structure of the cross-linker could potentially be replaced by renewable resources, further reducing the environmental impact of the system (Hardy, 2005).
The di-acid cross-linker is formed from the heating of dipropylene glycol in the presence of maleic anhydride and a schematic of the cross-linker produced is shown in figure 2.

![Figure 2. Schematic of maleic monoester used to cross-link ELO](image)

Once the oil and cross-linker are combined, the constituents will eventually harden at room temperature although this process will take a matter of days (Koelewijn et al, 2005) – the reaction is shown schematically in figure 3. An elevated temperature will of course speed up the rate of reaction.

![Figure 3. Schematic of reaction of ELO with crosslinker to form networked system](image)

Patents and papers (Kastl et al, 2000, Boquillon and Fringant, 2000) have described the production of a solid material from ELO in more detail. The present paper is concerned primarily with the performance of the system in flooring applications, after manufacture using elevated temperature and atmospheric pressure that can be converted simply to an industrial scale. The manufacturing method use is described in the next section.
3. Method of Sample Manufacture

In order to produce solid samples of known size, the two liquid components needed to be mixed together to form a specific volume of material. This would usually require around 500 ml of liquid to produce sufficient samples for the screening programme of tests.

The ELO and cross-linker were mixed thoroughly using a magnetic stirrer at 3000 rpm for 2 minutes. This speed and time were chosen as it has previously been shown to provide an effective mix (Koelewijn, 2005). This speed and time were also used in further trial experiments in which a vegetable dye was added and visual inspection suggested that the dye was distributed evenly after 2 minutes of stirring.

Previous experiments had shown that the system would be cured fully after a cure cycle of 150°C for 30 minutes (Koelewijn, 2005, Boquillon and Fringant, 2000). The mould to be used was pre-heated in an oven to 5°C above the desired temperature. The elevated temperature was required as there is a temperature fall when the oven door is opened. The mould was removed, the liquid poured into the mould and then replaced in the oven. However, immediately upon returning the mould to the oven, the temperature was reset to the desired value with a variance of ±1 °C, in line with typical processing controls on an industrial scale.

After the required amount of time, the mould was removed from the oven and the sample was removed. It is placed on a wire rack in order to allow full air circulation at room temperature.

There are no British Standards that describe the post-cure conditioning required for this particular system. However, there are examples within the standards for other plastics and these are used here. Plastics that have undergone cure often need to come to equilibrium, which is achieved through conditioning. In the present study samples were left at room temperature for 72 hours. This ensured that any resilient processes have completed in accordance with BS EN ISO 1798:1999.

For each set of samples, at least six specimens were produced- this is to ensure that there were at least five samples that are suitable for testing, as specified in BS 2846-2:1981 ISO 2602-1980.
Batches of samples were manufactured with a view to assessing the process variables indicated below

Molar ratio of components when cured at 150 °C for 30 minutes

Cure times at a molar ratio of 2.5:1 (Cross-linker: ELO) when cured at 180 °C

Cure temperatures at a 2.5:1 molar ratio (Cross-linker: ELO) when cured for 30 minutes

The 2.5:1 molar ratio was kept constant during the cure time and temperature parametric studies since simple stoichiometric considerations suggested that this ratio should give near-full cross-linking, although complete cross-linking would not be expected in practice because the mix hardens as cross-linking progresses and the mobility of the molecules decreases rapidly.

180°C is the temperature at which carpet backing systems are processed currently in order to cure the PVC applied. Therefore this temperature was used for comparison purposes and to assess the feasibility of substitution.
4 Tensile Tests

4.1 Test Method

Tensile tests are often used in the materials industry to give an indication of properties in service. During use, materials may be subjected to a number of loading regimes, e.g. short and long term, including fatigue and creep and dynamic impacts. These will affect the ability of that material to withstand further loading. Tensile tests are designed to replicate some of the extreme conditions and therefore give an indication of what will occur in practice.

These individual tests do not require a large amount of material, although it is important that a number of tests are conducted to verify significance.

The sample was then cut out using a hand press and cutter specified by BS EN ISO 1798. The material is cut into a dumbbell shape (see figure 4). This shape is used to provide a region of well-defined gauge length, in which the stress can remain constant during testing, and to reduce the likelihood of premature fracture at the grips of the machine.

![Figure 4. Dumbbell used in tensile test](image)

The cut samples are conditioned for 24 hours to ensure that the atmospheric effects are the same with each test. A controlled atmosphere is used for traditional flooring tests of 65 ±5 % RH and 20 ± 1 °C. It therefore seemed prudent to use this conditioning for the samples in each case, as well as testing in this environment.

After conditioning and cleaning off any loose particles, the central portion of the dumbbell was measured across the width and thickness to ± 0.1 mm. Three measurements were taken and the arithmetic mean value for the width and thickness calculated. Five samples were measured in turn and the results logged.

The gauge length was marked on the samples, approximately equidistant from the mid-point, not more than 50 mm ± 1mm apart (EN ISO 1798:1999).
The test specimens were then clamped in the Testometric Micro 350 calibrated by UKAS to ISO 5893 and BS EN ISO 7500-1:1999 to grade 0.5, taking care to align the longitudinal axis of the test specimen with the axis of the testing machine and to set the gauge length correctly. The samples were tested in accordance with BS EN ISO 527-1:1996 BS 2782-3: Method 321:1994 ISO 527-1:1993 in order to determine the tensile behaviour of the test specimens. The stiffness of the machine has been calculated by the manufacturers and is accounted for in the electronic calculation of the distance moved by the crosshead.

The test specimens were extended along its major longitudinal axis at a constant speed of 100 mm/min until fracture. Any fractures that occurred outside the gauge length, within 10 mm of the jaws or which were associated with an obvious defect were discarded.

The maximum force and elongation was measured electronically using the Testometric Micro 350 and a stress-strain graph could be derived, similar to the schematic in figure 5.

![Schematic stress-strain curve](image)

**Figure 5. Schematic stress-strain curve**

From the graphs, the properties of $\sigma_y$ (yield stress) and $\varepsilon_{max}$ (maximum strain) were then determined. The Young's modulus of elasticity was calculated from the stress at a strain of 0.0005 and the stress at a strain of 0.0025 (i.e. a secant modulus between 0.05 and 0.25% strain in accordance with BS EN ISO 527-1:1996).
These calculations were completed for each of the samples and the arithmetic mean and standard deviation were found.

4.2 Results and Discussion

4.2.1 Results

The results from the tensile tests are shown in figures 6 - 8. Figure 6 shows the effect of varying molar ratio at constant cure time and temperature, figure 7 shows the effect of varying time at a constant molar ratio and cure temperature and figure 8 shows the effect of varying cure temperature at a constant molar ratio and cure time. The data points represent the average of at least five tensile tests and the extent of the error bars indicate plus and minus one standard deviation. The solid lines highlight the trends of the data.

![Figure 6](image-url)

*Figure 6. Mechanical properties measured as a result of tensile tests on material cured at 150 °C for 30 minutes*
Figure 7. Mechanical properties measured as a result of tensile tests on material with a 2.5:1 molar ratio (diacid:ELO) cured at 180 °C

Figure 8. Mechanical properties measured as a result of tensile tests on material with a 2.5:1 molar ratio (diacid:ELO) cured for 30 minutes
Based on the results of the above tests, “best” and “worst” samples were identified. The best results were from a 2:1 molar ratio, cured at 150°C for 30 minutes (now termed sample A) which had a Young’s Modulus of approximately 6 MPa and a peak stress of just less than 2 MPa, although it did not have the highest strain to failure. The worst results were from a 1:1 molar ratio, cured at 150°C for 30 minutes (now termed sample B) which had a low Young’s Modulus and peak stress, with an associated low strain to failure. The tensile results for samples A and B are plotted in figure 9, together with results for a sample C, which is a PVC tile that has been used as a stand-alone flooring product. In summary, the samples were:

- Sample A- 2:1 molar ratio, cured at 150°C for 30 minutes
- Sample B- 1:1 molar ratio, cured at 150°C for 30 minutes
- Sample C- A PVC tile that has been used as a stand-alone flooring product

![Figure 9. Mechanical properties determined from tensile tests on samples also tested using traditional flooring tests](image-url)
4.2.2 Discussion

4.2.2.1 Effect of Varying Molar Ratio

It is clear from the graphs in the previous section that varying the process parameters has a significant effect on the properties investigated (Young’s Modulus, strain to failure and peak stress).

With regard to molar ratio, theoretically at a molar ratio of 2.5:1 all the reactive groups have combined to create the strongest polymer. If there are a larger number of cross-links, there will be a larger amount of force required to break these links and destroy the polymer, therefore the polymer will be stronger. However, it can be seen that the nominal peak stress tends to increase and then decrease with a peak at a ratio of diacid: ELO of approximately 2:1. There is a similar trend observed for the Young’s Modulus with a peak occurring at a ratio of approximately 2:1 followed by a sharp fall.

This peak can be explained if the mobility of the components is considered. In order for the reactive groups to combine, they must first meet. As the reaction occurs, a more viscous polymer begins to form. As the viscosity increases, the mobility of the components decreases and therefore there is less likelihood that the reactive groups will meet and combine further. There comes a finite point beyond which the mobility of the reactants is restricted and no further reactions can occur, despite an increase in cross-linker added to the system. At higher molar ratios, there will be excess diacid in the system. It is suggested that this will then act as a plasticiser and fill the gaps left by the cross-linking process. This is shown by the decrease in Young’s Modulus and peak stress beyond the 2:1 ratio.

The more diacid that there is available for cross-linking, the greater the likelihood that an individual reaction will occur and consequently, the greater the amount of cross-linking. If there are more cross-links in one system than another, it will have a greater Young’s Modulus and strength. This is because there is more force required to stretch and break the higher density of bonds.

4.2.2.2 Effect of Varying Cure Time

Figure 7 shows that at 180 °C increasing the cure time has a dramatic effect on Young’s Modulus. There is a less obvious effect seen on the peak stress and strain to failure.
As described above, mobility and curing is an issue as the two components are mobile in the liquid form and must meet for the reactive groups to combine to form a solid polymer. These areas of solid polymer forming in the two liquid components cause the liquid to be more viscous and therefore the remainder of the reactive groups are less mobile as reaction time continues.

Visual observation suggested that the material was solid after 5 minutes conditioning at 180°C. Beyond these five minutes it is argued that the reactants are not sufficiently mobile to create any new cross-links between independent molecules. Heat is continuously added to the system as it is held at elevated temperature. This heat energy may be used by the system in other ways, such as increasing the number of cross-links with neighbouring molecules and therefore increasing the stiffness and strength of the system.

The peak stress continues to increase gradually with cure time, whereas strain to failure remains relatively stable. It is theorised that this is because the strain will not increase any further with additional cross-linking.

It has already been shown that the peak stress and Young’s Modulus at 150 °C for 30 minutes occurs at a 2:1 ratio. Therefore it is theorised that there is excess diacid in this system. With the heat energy input this excess diacid may react further with the ELO, although a lack of mobility may restrict these reactions.

There is a plateau in the Young’s Modulus and peak stress that occurs after 20 minutes. It may be that beyond this time there are no further reactions that can occur as neighbouring molecules have reacted as fully as they are able. Therefore the stiffness and strength will not increase further.

4.2.2.3 Effect of Varying Cure Temperature

Figure 8 shows the effect of altering cure temperature on mechanical properties. It can be seen from this graph that there is little change in peak stress with an increase in temperature. There is also little change in the strain to failure. However, Young’s Modulus falls slightly with an increase in temperature.

It was shown by the previous experiments that after 5 minutes at 180 °C the system had become solid. It is theorised that at these cure temperatures the systems would also have been cured at times much less than 30 minutes. The visual observation of the cure indicates that the reactants are no longer mobile and therefore cross-links between different molecules are unlikely. There may however, be further cross-linking between neighbouring molecules.
At greater temperatures, with excess diacid, it is theorised that there are a greater number of reactions that become available, as the activation energy required is surpassed. If a greater number of reactions are possible, then the material will become more viscous more quickly and mobility of constituents will be lost.

The excess diacid may also react with individual ELO molecules, creating shorter chain molecules and a less stiff structure. This would explain the slight drop in Young’s Modulus, with little effect on the peak stress.

4.2.2.4 Tensile Tests of Samples used for Flooring Tests

The tensile tests gave some indication of performance to be expected in service. The next part of this investigation is to verify that this is the case. The two samples chosen from the tensile tests were compared with a PVC tile that is sold as a single polymer product. The results are shown in figure 9.

The tensile tests showed that Sample C, the PVC product, had a markedly higher Young’s Modulus, peak stress and peak strain that the other samples. Sample A had properties that were approximately twice that of sample B. Therefore it would be expected that sample C would outperform both the ELO system samples in the flooring tests, described in the section below.

5 Flooring Tests

5.1 Test Methods

Flooring products can be tested using a variety of methods to assess if they are ‘fit-for-purpose’. These tests are designed to ensure that the customer receives a product that is suitable for their needs and this is often specified through the use of a grading system. The grading system for the carpet industry will assign a number which designates the level of use that a carpet can undertake in practice—from heavy contract to light domestic use. The flooring tests result in a grading between 1 and 5, relying on the expert judgment of professionally trained assessors through visual assessment, where 5 is the best in terms of fitness-for-purpose under heavy contract use. Two tests used in this investigation were the Vetterman drum test and the Lisson-Tretrad test.

British Standard BS ISO 10361:2000 describes the Vetterman drum and hexapod tumbler tests. They both work on the same principle of simulating the conditions of use. The Vetterman drum is a large apparatus that revolves with a steel ball inside. This ball has rubber feet, designed to fatigue the flooring which is lining the inside of the drum. A circular brush constantly removed broken fibres. The apparatus is shown in figure 10.
The Lisson-Tretrad test (BS EN 1963:1998) also describes a method of abrasion resistance measurement (see figure 11). A series of rubber feet are loaded and slipped on the flooring, similar to the scuffing that might be expected from dragging shoes.

After each test the flooring was then assessed for changes in appearance and graded by a professionally qualified assessor.
Another important test in the flooring industry is the resistance to the application of a static load. In the lifetime of a flooring product there are often a number of heavy pieces of furniture that will provide a consistent heavy load.

BS 4939:1987, ISO 3416-1986 describes a method of testing designed to measure this effect. A known pressure was applied to the sample of flooring, through the use of a heavy load and circular foot for 1 hour. The resulting loss of thickness was measured and recorded. The load was then re-applied for a further 23 hours. After the load was removed, the appearance was again assessed.

5.2 Results

The results of the static loading, Vetterman drum and Lisson-Tretrad tests are presented in Table 1.

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<td></td>
<td>Shade</td>
<td>5</td>
<td>3</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>Overall change of appearance</td>
<td>5</td>
<td>3.5</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>Final rating</td>
<td>5</td>
<td>3.5</td>
<td>5</td>
</tr>
</tbody>
</table>

Table 1. Results of flooring tests. Where grading is shown it is scaled 1-5, where 5 is suitable for heavy contract use, 4 is suitable for medium contract use, 3 is suitable for light contract use and 1-2 are domestic ratings reserved for the home market.
5.3 Discussion

The static loading test results were performed on similarly-sized material as would be expected in practice. These show that sample A performed slightly better than C, which in turn was considerably better than sample B. However, all samples received a grade 5 based on their performance.

All of the samples performed particularly well in the Vetterman Drum test after 5,000 revolution, achieving a grade 5. However, after a complete cycle of 22,000 revolutions sample B was considerably worse than the other samples. Sample A and C remained comparable with only a slight variation in performance.

After 400 cycles on the Lisson-Tretrad test samples A and C both achieved a top grading. Again, sample B achieved a slightly poorer rating of light contract. However, even this grading could be acceptable.

The tests showed that sample A and C would have been passed at a heavy contract rating- suitable for any number of applications in practice. The results from the flooring tests shown in table 1 can be compared with the tensile test results shown in figure 9. The tests show the comparison between two resins cured at 150 °C for 30 minutes with different molar ratios (2:1 and 1:1, samples A and B respectively) and the PVC tile- sample C.

It was clearly seen that sample C had a much higher Young’s Modulus, peak stress and strain to failure than the resin samples. Sample A, the 2:1 molar ratio, also had appreciably higher properties than sample B, the 1:1 molar ratio.

It might therefore be predicted that sample C would perform significantly better in the flooring tests than the resin samples. However, it was seen that both sample A and C perform well, achieving a level 5 (heavy contract) in a number of categories. Given that the mechanical properties were so dissimilar, with sample C performing exceptionally well, this result is surprising.

In the example of these particular tests it can be seen that sample A is fit for the purposes of these tests and would be passed as a level 4.5. Sample A is therefore adequate for the purposes of flooring. It is suggested that the performance of PVC in these tests far exceeds that required for the most demanding contract use since it achieved the highest grading in a number of tests.

It is still debatable exactly which combination of Young’s Modulus, peak stress and strain to failure would be more beneficial for a flooring product. It is anticipated that a combination of both would be preferable and this has been validated by the preliminary flooring tests.
6 Concluding remarks

ELO, processed with a cross-linker has been investigated as a potential flooring material. To do this the effect of process parameters on material properties has been used as a preliminary screening to identify candidate materials for more extensive flooring investigations.

It has been shown that altering processing parameters of this system can be effective in changing material properties. Strain increases with increasing molar ratio, whereas the Young’s Modulus and peak stress peak at the 2:1 molar ratio (Cross-linker :ELO). It has also been shown that increasing cure time will have a dramatic effect on Young’s Modulus, but less so on peak stress and strain to failure. Altering the cure temperature during a 30 minute cure time has little effect on the mechanical properties.

The compliment of flooring tests have shown that the material manufactured from ELO and the cross-linker can pass a heavy contract rating. The ELO system is therefore fit for the purpose of providing a flooring surface, albeit at different ratings depending on processing parameters. The system has been shown to be competitive for performance against a PVC tile when used as a flooring material.
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