The assessment and behaviour of crack bridging and crack accommodating protective coatings on reinforced concrete

by

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Abstract

The ingress of carbon dioxide and chloride ions into reinforced concrete can cause corrosion of the steel reinforcement. Cracks and poor quality cover can accelerate this process. Coating the surface of the concrete can increase the life of the structure. A coating must have the ability to bridge cracks that form in the substrate concrete and to accommodate any subsequent movement of that crack without failure. If the coating itself is damaged by substrate cracking then the coating becomes less effective as it no longer provides a barrier to the deleterious agents.

There are currently few methods to assess the performance of a coating on a reinforced concrete surface subject to crack formation and subsequent movement. In this thesis a test specimen, machine and methodology are developed to evaluate the crack bridging and crack accommodation performance of these coatings. The specimen is 40mm x 40mm x 160mm mortar prism, coated on one face and axially reinforced with an 8mm steel bar. A crack in the specimen is opened by the application of a tensile load to the ends of the reinforcing bar by a pneumatically powered testing machine. Initial investigations confirmed that the testing machine was reliable and gave reproducible results. A testing program was then carried out to investigate the effects of temperature, coating thickness, artificial weathering and crack width on the crack bridging and crack accommodation behaviour of the coatings. It was found that increasing the thickness of a coating allowed wider cracks to be bridged. Crack accommodating behaviour was found to fall into three regions dependent upon the test temperature. At the lowest temperatures both crack bridging and crack accommodation did not occur. As the temperature was increased crack bridging and crack accommodation occurred but the crack accommodation behaviour was highly variable. As the temperature was increased further a region is encountered where reliable crack bridging and crack accommodation occurred and the variability in crack accommodation behaviour was reduced. Artificial weathering was found to have a detrimental effect on both crack bridging and accommodation performance.
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Glossary

Abbreviations

OPC.... Ordinary Portland Cement
LVDT... Linear Variable Differential Transformer
QUV...... suffix - Specimen has been artificially weathered in a QUV Weatherometer
DMTA..... Dynamic Mechanical Thermal Analysis/Analyser
BRE..... Building Research Establishment
RT...... room temperature
rh....... relative humidity
psi....... pounds per square inch
Hz....... frequency, Hertz
µ......... micro, 10^-6

Symbols

α........ linear thermal expansion coefficient
τ........ shear stress
γ........ shear strain
G........ shear modulus
J.......... elastic compliance
E.......... Youngs modulus
w........ crack width
a........ crack length
σ........ stress
T.......... temperature

\( t \).......... time
\( t_0 \).......... initiation time
\( t_1 \).......... propagation time
η.......... viscosity
Hz......... frequency
\( \tan \delta \)..... loss tangent

\( U \).......... strain energy release rate
K ........ stress intensity factor                       MPa m\(^{0.5}\)
L ........ length                                        mm, m

Superscripts

  a ........ crack opening of 0.07 - 0.29mm
  b ........ crack opening of 0.2 - 0.4mm
  c ........ 3000 light hours artificial QUV weathering
1. Introduction

Concrete is used in many forms of construction today. Its use is immediately apparent in concrete buildings and bridges but less so in other structures such as steel or timber frame buildings which often have mass concrete foundations. Brick and stone buildings use a micro-concrete adhesive in their construction and steel structures may also be protected against fire by a surface coating of concrete. Concrete is a versatile building material that can be easily moulded into large structures quickly and cost effectively and has been used as a construction material for many generations. The Egyptians were using it 2000BC, Pomeroy. Lime based mortars have been found to have been used for the floors of huts dated 5600 BC. The Pantheon, built in Rome in 27 BC, has an unsupported dome 50m in diameter constructed of lightweight concrete segments. The aggregate was volcanic pumice bound in a lime and pozzolana cement. More recently, in 1759, the Eddystone lighthouse was built on a concrete foundation. The cement was made from burnt Welsh limestone and an Italian pozzolana. Modern concretes can trace their origin to the work of Joseph Aspdin who patented Portland cement in 1824.

These early applications have been in the form of an adhesive or as mass concrete where use is made of its excellent compressive strength. The use of concrete can be extended to include tensile loading if it is reinforced with a suitable amount of steel bar. However, it is with the addition of steel reinforcement that problems can begin to occur. The unreinforced dome of the Pantheon has been standing for 2000 years but many reinforced concrete structures built in the last 30 years are in a poor state of repair.

Properly designed reinforced concrete is a potentially durable material and can be expected to retain its structural integrity for many years under normal circumstances. This durability stems from the fact that steel in concrete with a pH of at least 9.3 is in a passive state and will not corrode. However, if the pH drops below this level corrosion can occur. (As oxygen and water are normally present in concrete a galvanic corrosion cell is possible).
Correctly designed reinforced concrete will ensure that a passive state is maintained over the design lifetime of the structure. If the concrete is too permeable or the depth of cover over the steel reinforcement is too small, carbon dioxide or chloride ions may penetrate the concrete cover to the depth of the reinforcement. If carbon dioxide enters the concrete carbonation can occur. This is a process in which the alkaline calcium hydroxide in the concrete is replaced by calcium carbonate, reducing the pH. If the carbonation front reaches the reinforcing bar and the pH falls sufficiently corrosion can occur. If chloride ions reach the reinforcing bar the passivity is again destroyed and corrosion can occur.

The corrosion products which form have a larger volume than the steel that is consumed and so stresses may be set up within the concrete. These stresses may be large enough to cause the concrete to crack or break away from the reinforcing bar. The damaged areas of concrete allow greater access to carbon dioxide and chloride ions and so offer less of a barrier to corrosion. Cracks that form as a result of drying shrinkage, bad design or loading during use can also have this effect.

If these paths for the deleterious agents can be restricted or removed, the durability and lifetime of the structure may be increased. The sealing of un-cracked concrete with hydrophobic treatments or pore blockers can reduce the ingress of deleterious agents by restricting moisture uptake and movement. However, if the concrete cracks, paths again exist into the bulk of the concrete for these agents. When concrete treated with penetrating treatments cracks, new surfaces are formed that are not treated.

Coatings can also be used and if the concrete is sealed with a substance that can bridge cracks, the durability of the structure is not compromised. In addition to bridging a crack, which only requires the coating to deform once as the crack opens, it may also be required to accommodate the repeated movement of an active crack. Cracks may be active due to thermal or load cycling. The extent to which the material can bridge cracks or accommodate crack movement depends upon the temperature, crack width, coating thickness and material type.
In order to be able to evaluate such coatings for crack bridging and crack accommodating performance and to compare them, a reliable testing method is required. This work details the design, construction and evaluation of such an apparatus and method. Once the apparatus and method had been proven to be both reliable and reproducible, tests were carried out on different materials to evaluate their performance and the factors that effect this performance.

A testing program was undertaken on commercially available protective coatings of various types to assess their crack bridging and crack accommodating performance. Various conditions of temperature, artificial weathering, thickness and crack opening were used.

The objectives of this work were:

i/ to design a test specimen, testing machine and test method with which to evaluate the crack bridging and crack accommodating behaviour of protective coatings for reinforced concrete.

ii/ the test specimen should represent the type of substrate to which the coating would be applied in use.

iii/ to assess the influence of coating thickness and type, crack width, cyclic crack movement, weathering and temperature on the crack bridging and crack accommodating behaviour of these protective coatings.
2. Literature review

This chapter presents a review of literature relevant to this work. It covers the process of electro-chemical corrosion of steel in reinforced concrete, the role played by cracks in the concrete and the protection of reinforced concrete by various types of surface treatment. Presently available procedures to assess the damage caused to surface coatings by the substrate concrete cracking are critically reviewed and a number of requirements for an assessment methodology are derived. The properties of polymeric materials are examined with reference to changes in temperature and artificial weathering.

Concrete is a material whose basic properties may be modified by altering the proportions of its constituents and by additions of other materials. It is a brittle material and has a relatively low tensile strength. To improve its performance in tension and bending it is commonly reinforced with steel in the form of bars. The passivity of this steel reinforcement is important to the durability of a structure. The destruction of the passivity by carbonation and chloride attack, through the ingress of carbon dioxide and chloride ions, is a serious problem. The subsequent corrosion processes and the role of cracks in these processes are important considerations in structural design and maintenance. A reduction of the impact of reinforcing bar corrosion can be achieved by the use of surface coatings to the concrete. It is necessary to assess the durability of these surface coatings to predict service life and performance. Several methods for the evaluation of coatings for various applications are in existence. A selection of these have been reviewed to formulate a general set of requirements to assess the durability of surface coatings specifically for use on reinforced concrete structures.

2.1. Reinforced concrete

Many structures, for example bridges and large buildings, have been built using reinforced concrete due to its versatility, ease of use, and low relative cost. When designed and used correctly it is a very durable material and requires little maintenance. Soroka defines
durability as "the ability to withstand the damaging effects of the environment and of its service conditions without deterioration for a long period of time." However, concrete is often misused either through carelessness or ignorance leading to reduced durability. Even though the quality of the cement powder is guaranteed by the manufacturer, it is the concrete made from it that is the building material and its quality is almost exclusively dependent on the workmanship of concrete making and placing, Neville.

Ordinary Portland Cement (OPC) Concrete is a composite material made from varying proportions of aggregate, water and OPC. Admixtures may be used to alter the properties of the fresh and hardened concrete. Accelerators increase the rate of the hydration reaction of the OPC to allow the early removal of formwork and retarders reduce the rate of evolution of heat in mass concrete to reduce the risk of cracking. Plasticisers increase the workability of the fresh concrete and air entrainers reduce the susceptibility to freeze/thaw damage. The properties of the concrete may also be altered by varying the proportions of the basic constituents. In general, the lower the free water/cement ratio the higher the strength, Table 2.1.

<table>
<thead>
<tr>
<th>Free water/cement ratio</th>
<th>0.40</th>
<th>0.45</th>
<th>0.50</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compressive Strength (MN/m²)</td>
<td>59</td>
<td>57</td>
<td>52</td>
</tr>
</tbody>
</table>

Table 2.1. 28 day compressive strengths of 1:3 concrete made with High Early Strength Portland Cement, after Agrement Board.

The relatively high compressive strength of concrete is offset to some extent by its low tensile strength. For example, a concrete with a compressive strength of 50 MN/m² may only have a tensile strength of 3.5 MN/m², Price. When placed in compression concrete behaves in a predictable way but whilst in tension it behaves in a brittle manner. Hence it is important that if concrete is used such that it is put into bending or tension steel reinforcement is used to carry these tensile loads.

2.1.1. Corrosion of steel reinforcement

Although water and oxygen may be present at the reinforcing steel surface a layer of concrete of a suitable water/cement ratio and thickness, properly compacted and cured...
should provide excellent protection for reinforcing steel against corrosion, *Robbery*. The pore fluids within ordinary portland cement pastes normally have a pH of at least 13, *Barneyback and Diamond*. According to the Pourbaix diagram for iron at this pH it should be in a passive state over a wide range of potentials, *Pourbaix* and *Hansson*. This means that the steel will not corrode. To understand why iron is passive under certain conditions it is necessary to look at the corrosion process itself. At pH 7 in an aerated solution containing excess oxygen the corrosion reactions shown below in reactions 2.1 and 2.2 occur.

### Anodic Reaction

\[
Fe \rightarrow Fe^{2+} + 2e \quad (2.1)
\]

### Cathodic Reaction

\[
O_2 + 2H_2O + 4e \rightarrow 4(OH^-) \quad (2.2)
\]

These reactions take place at discrete anodic and cathodic sites on the reinforcement. The ferrous and hydroxide ions formed in reactions (2.1) and (2.2) react to form ferrous hydroxide, thus:

\[
Fe^{2+} + 2(OH^-) \rightarrow Fe(OH)_2 \quad (2.3)
\]

The ferrous hydroxide so produced is then oxidised to produce hydrated ferric oxide.

\[
4Fe(OH)_2 + 2H_2O + O_2 \rightarrow Fe_2O_3.3H_2O \quad (2.4)
\]

Several other reactions are possible at the anodic and cathodic sites depending on the amount of oxygen and the pH at the iron surface, *Hansson* and *Foroulis*, and consequently several different reaction products may be formed. When the pH of the concrete is greater than 9 the hydroxide/hydrated oxide layer that forms on the surface of the iron is stable. This layer stops any further corrosion from taking place. The iron is then said to be in a passive state. The question then arises, why should steel reinforcement in concrete corrode at all?
The passive oxide film that forms on the steel surface at high pH protects it from further corrosion. If this passivity is somehow destroyed, the concrete will provide nearly ideal conditions (oxygen and water) for an electrochemical corrosion cell to exist and so reinforcement corrosion can occur. Two ways in which the passivity may be destroyed are (i) carbonation and (ii) chloride attack.

(i) Carbonation

Carbonation is the diffusion of carbon dioxide into the concrete cover. The carbon dioxide combines with the pore water to form carbonic acid. This acid combines with the calcium hydroxide from the OPC to form calcium carbonate and water, reducing the pH of the pore water, Bob. Once the pH of the pore water falls below 9 the steel is no longer in a passive state.

\[
\text{CO}_2 + \text{Ca(OH)}_2 \rightarrow \text{CaCO}_3 + \text{H}_2\text{O}
\]  

(2.5)

This allows the steel to corrode as the oxygen and moisture requirements are fulfilled.

(ii) Chloride attack

Chloride attack is the migration of chloride ions through the concrete cover to the reinforcing bar surface. Here they are adsorbed onto and penetrate the oxide film on the bar surface resulting in a large increase in the conductivity of the film, Hoar, thus allowing corrosion to occur.

This migration can occur by two mechanisms, capillary uptake and diffusion. Capillary uptake is the movement of chloride ions in aqueous solution into the concrete. This is possible because concrete has an internal structure that is made up of connected and non-connected pores, capillaries, and voids that makes it permeable. Permeability can be reduced by making concrete using a low free water/cement ratio, an adequate cement content, an impermeable aggregate of good grading, good compaction and good curing, Hannant. Diffusion occurs when chloride ions are able to move through concrete saturated with water along a concentration gradient. Clearly, if the permeability of the concrete and hence its water content can be reduced, chloride attack can also be reduced.
If the reinforcement corrodes it can cause a variety of problems. These may be purely cosmetic in nature, for example rust staining of the surface of a structure. In this case no loss of strength occurs but the structure may need to be cleaned or painted. More serious damage may occur depending upon the severity of the corrosion. Corrosion of the steel reinforcing bars yields iron oxides and hydroxides that have greater volume than the iron that has corroded, Verbeck. Spalling of the concrete cover due to the formation of these voluminous corrosion products may occur. This may again lead to non-structural damage although falling concrete may constitute a hazard to pedestrian or vehicular traffic. At the other extreme it could lead to loss of strength of the concrete and accelerated corrosion of the reinforcing steel reducing its strength. Severe loss of concrete or steel cross-section can lead to a loss of structural integrity.

![Figure 2.1. Relationship between initiation and propagation times, after Tuutti.](image)

Tuutti has suggested that reinforcement corrosion occurs in two time periods, Figure 2.1

i) Initiation, and

ii) Propagation
Chapter 2: Literature review

The initiation time, $t_0$, is the time it takes for the depassivating agents to reach the reinforcing steel and start the corrosion process. The propagation time, $t_p$, is the time for which corrosion takes place until repair is necessary or failure has occurred. Once initiated the corrosion process is controlled by the rate of the cathodic reaction which in turn is controlled by the transport of oxygen and water through the concrete to the cathodic sites on the bar. If there is sufficient density and thickness of concrete cover over the reinforcing bars the corrosion process may be slowed down or stopped, Beeby (1983).

2.1.2. The role of cracks in reinforcement corrosion

Since the destruction of the steel passivity relies on substances moving through the concrete to the reinforcement it follows that if the concrete is cracked this process will be accelerated to some extent, by providing less of an obstacle to this movement.

There are two theories concerning the role of cracks in reinforcement corrosion, Darwin et al:

*Theory number 1*

Cracks significantly reduce the service life of a structure by permitting the access of chloride ions, water and oxygen to the steel, not just reducing $t_0$, but providing space for the deposition of the corrosion products.

*Theory number 2*

Cracks may reduce $t_0$, but corrosion is localised and confined to the intersected bar. Also since chloride ions and carbon dioxide eventually penetrate un-cracked concrete anyway and initiate corrosion, after a few years service life there will be little difference between the amount of corrosion in cracked and un-cracked concrete, i.e. cracking has little effect on $t_p$.

Cracks exhibit certain properties that may be expected to influence their effect on corrosion. The origin of the crack may be important. If the crack width does not vary with time, for example a plastic shrinkage crack, it may heal autogenously or may become plugged with
Dust. Autogenous healing may occur with a stationary crack in the presence of moisture, Lauer. Autogenous healing occurs by the carbonation of calcium hydroxide in the cement paste and by the hydration of un-reacted cement. Crystals of calcium carbonate and calcium hydroxide form in the crack and effectively plug it. This is unlikely if the crack is active and the crack width varies with time, for example a crack caused by traffic loading or thermal expansion.

Schiessl showed that for a given environment and crack width, if there were only a few cracks in the structure, the probability of obtaining a crack with a high degree of corrosion was considerably reduced. However, in the same situation but with a greater number of cracks the probability of finding extensive reinforcing bar corrosion was much greater. This suggests the frequency of cracks may be an important factor.

The orientation of the crack with respect to the reinforcing bars may also be an important factor. If the cracks are transverse to the reinforcing bars, the crack may intersect several bars but will only expose small portions of each one. In this case corrosion was limited to about three bar diameters along the bar from the crack, Beeby (1978). On the other hand cracks parallel to and coincident with a reinforcing bar greatly increased the risk of corrosion, Darwin et al. In this case there is no way to confine the corrosion process and corrosion may proceed unchecked and possibly even accelerate with time. The most common cause of this sort of cracking is plastic settlement where cracks form immediately above and parallel to the reinforcing bars.

The width of cracks is important when considering their effect on corrosion. The sides of cracks are not parallel from the concrete surface to the bar surface and so crack shape should be considered when specifying crack widths. Most specifications for reinforced concrete, for example those relating to bridge decks, give limitations on crack widths at the concrete surface. It should not be assumed that there is a unique relationship between crack widths at the concrete surface and crack widths at the bar surface, Beeby (1978). It is the crack width at the bar surface that is important when looking at reinforcing bar corrosion.
because it is here that the bar is actually exposed. However, it is at the bar surface that the crack width is most difficult to measure when examining a structure non destructively.

Exposure tests carried out at the Technical University, Munich give an idea of the relationship between crack widths and the amount of corrosion. The test used reinforced concrete beams that had been loaded to give crack widths of up to 0.4mm. The beams were exposed to urban, heavily polluted industrial and marine environments. Beams from each environment were broken open and the corrosion examined after 1, 2, 4 and 10 years. Rehm and Moll report that after 2 years exposure cracks of greater than 0.1mm in width rarely showed corrosion, while it was always present at 0.25mm wide cracks. After 10 years, the influence of crack width was found to be small. Based on this data Schiessl concluded that over the design life of a structure, crack width had no significant statistical influence on the rate and extent of reinforcing bar corrosion. Schiessl was referring to cracks that are transverse to the reinforcing bar direction. He was also using crack widths measured at the concrete surface which Beeby (1978) has pointed out are not necessarily the controlling factor. Further, this argument is not applicable to cracks that run parallel to and coincident with the reinforcing bar.

The question now arises, how much of a problem is cracking? Theory one suggests that cracks significantly reduce the service life of a structure. Theory two suggests that cracks do not significantly effect the service life of a structure as chloride ions and carbon dioxide would penetrate the concrete anyway and cause corrosion. If theory one is correct we should take great pains to reduce cracking to a minimum. If theory two is correct cracks only reduce the initiation time for corrosion to start and so there is little point to going to the bother of controlling cracking below the level at which it is a structural problem, as it would just be a cosmetic defect. Cracking in reinforced concrete structures can be controlled to a certain extent by careful design of the mix, the reinforcement and the structure as a whole. These measures are only useful in the design and construction stage and cannot be implemented at a later date.
If it were possible to permanently reduce or stop the transport of chloride ions and carbon dioxide into the concrete corrosion could either be significantly delayed or prevented from occurring. Further to this, if the transport of water and oxygen to the cathodic areas of the reinforcing bars could be reduced or stopped the rate of corrosion could either be reduced or stopped altogether. A method of achieving this would be to apply a barrier to the surface of the concrete that was semi-permeable or impermeable to either the corrosion causing or sustaining agents.

2.2. Protection of reinforced concrete using surface treatments

Reinforced concrete can be protected by certain treatments that are applied to the concrete surface. There are several commercially available surface treatments for concrete structures. Apart from those applied to increase durability by covering cracks and preventing the ingress of destructive agents, they may also be applied for several other reasons including covering up repairs, altering colour, or to stabilise friable surfaces. This work is concerned with the type of surface treatment used to increase concrete durability. Several types of these treatments are available. *CIRIA technical note 130* gives the following definitions:

*Penetrant - pore liner*

A low viscosity fluid that penetrates into the concrete, lines the pores and prevents the ingress of water. The majority of these substances are based on monomeric alkylalkoxysilanes and oligomeric alkylalkoxysiloxanes, commonly known as silanes and siloxanes respectively. Silanes become reactive in the presence of moisture, the speed of reaction being governed by the surrounding pH. In normal alkaline concrete, the silane reacts with the pore lining quite rapidly *McGill*.

*Penetrant - pore blocker*

A low viscosity solution that penetrates 1 - 3mm into the concrete. Some of these materials react with the concrete substrate to form crystals. Other low viscosity fluids, for example resins and drying oils, penetrate into the pores and harden. Pore
blockers impede the passage of water vapour and other gases to a greater extent than do the pore liners. Examples of these materials are silicates, silicofluorides, epoxy resins and acrylics.

**Sealer**

These materials are more viscous than the penetrants and form a thin film on the surface of the concrete as well as penetrate into it. These materials have good adhesion to the concrete and are sometimes used as primers for coating systems. Epoxy resins, polyurethanes, acrylics and linseed oil are typical examples of this type of material.

**Coating**

A material applied as a viscous liquid which forms a film on the surface of the concrete, with little penetration of the pores. Thin coatings 0.3mm to 1.0mm thick follow all unevenness of the concrete. Weathering and protective properties of the coating are dependant upon its formulation. Examples of these materials are epoxy resins, polyurethanes, alkyds, vinyls, acrylics, chlorinated rubber, styrene-butadiene, cement based stone paints, bitumens and combinations of these.

**Rendering**

This type of treatment is a thick coating usually applied by trowel as opposed to brushing or spraying as with the previously mentioned coatings. Some systems include a crystal growth pore blocker that migrates into the concrete substrate to improve its barrier properties. They are usually extended with inert fillers to provide weathering resistance but adhesion to the concrete substrate may be inferior to other types of treatment. Polymer modified cement mortars and crystal growth systems are typical examples of this type of treatment.

This work will deal with the coating type of surface treatment. Preventing the ingress of carbon dioxide, chloride ions and other deleterious agents is clearly beneficial for the durability of reinforced concrete structures, Roberty. Keeping concrete in a reasonably dry
state is also beneficial in restricting Alkali Silica Reaction and freeze-thaw damage. Equally clearly, cracks which cause breaks in coatings or which locally reduce water repellency of the surface become paths for moisture and potentially destructive agents.

2.2.1. The resistance of surface coatings to damage by cracking

Breakage of the surface coating due to substrate cracking will cause the coating to fail to perform properly. An ability to bridge cracks is therefore among the many parameters influencing coating selection suggested by Brown, Table 2.2, Robery, Englefried, Hewlett, Leeming, Swamy and Tanikawa and Harwood. It is also listed as one of the benefits of bitumen when used as a protective coating, Biczok. Robery suggests that case histories that include crack bridging performance data are required to allow coating specifiers to select satisfactory coatings.

A coating that can remain unbroken when a crack forms in the substrate is said to be crack bridging. It must also be capable of withstanding the repeated open/close cyclic fatigue movements in the case of active cracks without failure. In this case the coating is said to be crack accommodating. These definitions will apply to the remainder of this work. Crack bridging and crack accommodating behaviour are discussed in Chapter 5. If the crack is not active the coating needs only to be crack bridging. However, when the crack is active the coating also needs to be crack accommodating. If it does not fulfil one or both of these conditions it will no longer form a barrier to the destructive agents it was applied to exclude. This brings us to the position that a test is required to evaluate and compare the performance of these coatings regarding their crack bridging and crack accommodating ability.

2.3. The assessment of crack bridging and crack accommodating ability

A review of the literature has shown that there are several methods in existence to evaluate the ability of various surface treatments to bridge and accommodate cracks on concrete under various conditions. The test methods described all use a 'crack' in a substrate
although the substrate may or may not be cementitious in nature. Cracks may be formed before or after the application of the surface treatment. The tests also differ in the way the crack is opened and closed. This may be achieved through a fatigue machine, by the heating of metal sections or by the thermal expansion of the substrate itself. Both static and dynamic test procedures are used. Weathering, natural or artificial, may be used either before or during the test procedure.

<table>
<thead>
<tr>
<th>Protection</th>
<th>Durability</th>
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<tbody>
<tr>
<td>Diffusion of CO₂, chloride, O₂, sulphate</td>
<td>Proven use on concrete</td>
</tr>
<tr>
<td>Acid resistance</td>
<td>Case histories</td>
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<tr>
<td>Water vapour permeability</td>
<td>Ability to span over passive cracks</td>
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<tr>
<td>Water permeability</td>
<td>Ability to seal live cracks</td>
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<td></td>
<td>Durability under strong UV., rain/wind, condensation, temperature and immersion cycles, freeze/thaw, salt crystallisation</td>
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<tr>
<th>Application</th>
<th>Cost</th>
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<tbody>
<tr>
<td>Tolerance to surface preparation, moisture on application and during cure</td>
<td>Special application needs</td>
</tr>
<tr>
<td>Resistant to alkaline conditions</td>
<td>Relative cost/benefit at applied thickness</td>
</tr>
<tr>
<td>Ease of application, toxicity, flammability</td>
<td>Maintenance period</td>
</tr>
<tr>
<td></td>
<td>Ease of re-coating</td>
</tr>
</tbody>
</table>

Table 2.2. Coating selection criteria, after Brown.

2.3.1. The evaluation of the crack bridging ability of exposed roof coatings

"The flat concrete roof, finished with normal or foam concrete is the most common type of roofing in Israel as in other Middle Eastern countries", Jaegermann and Puterman. The roof is conventionally waterproofed with an in-situ applied bituminous fibre reinforced membrane. This is normally white washed to reduce heating in the summer. Active cracks are common in this type of roof due to thermal cycling. These cracks are a major cause of leakage because conventional non-elastic membranes loose their ability to bridge and accommodate cracks due to the intense ultra-violet radiation to which they are subjected.
This test procedure is an accelerated test to assess crack bridging and accommodating ability under real external exposure conditions.

The test substrate is made from a reinforced concrete slab measuring 1000 x 500 x 30mm to which aluminium profiles, painted black, are attached, Figure 2.2. The slab has a 30mm high edge running around its perimeter. A crack inducer in the form of a metal plate is cast into the bottom of the slab half way along its length. A crack may be induced in the slab before or after membrane application. To allow free movement of the two parts of the cracked slab the reinforcing bars are cut alternately 75mm either side of the crack inducer and enclosed in plastic tubes filled with lubricant. The two parts of the slab are also supported on pipes that are free to rotate. The aluminium profiles are attached to steel strips cast into each end of the slab. The profiles are enclosed in transparent topped boxes to increase the temperature they reach on solar exposure. The expected changes of crack width ΔL, can be calculated from the following equation:

\[ \Delta L = \alpha_1 L_1 \Delta T_1 - \alpha_2 L_2 \Delta T_2 \]  

(2.6)

where:

\[ \alpha_1 = 2.5 \times 10^{-5} (\kappa)^{-1} \]

\[ \alpha_2 = 1.0 \times 10^{-5} (\kappa)^{-1} \]

L\textsubscript{1,2}=800mm

Subscripts 1 and 2 refer to aluminium and concrete respectively, L is the initial length, ΔT is the change in temperature and \( \alpha \) is the linear thermal expansion coefficient. Assuming that the aluminium profile heats up from a night time temperature of 22°C, at which the crack is closed to a day time temperature of 80°C and the whitewashed membrane covered concrete heats up to 32°C (air temperature 30°C) it can be seen that the profile expands by approximately 1.2mm whereas the whitewashed concrete expands by 0.08mm giving a theoretical crack opening of about 1.1mm. If the membrane is not whitewashed the average temperature of the concrete slab will rise to approximately 45°C giving rise to an expansion of 0.18mm resulting in a theoretical crack opening of 1.0mm. This
shows that the membrane colour does not affect the daily crack opening by more than 10%. With air, aluminium profile and membrane temperatures of 30, 70-80 and 47°C respectively the crack opening was 0.7 ± 0.1mm with no significant dependence on membrane colour, this value being repeatable. The authors suggest that friction in the system is responsible for the actual crack opening being less than the theoretical opening. In use the aluminium profiles heat up relatively quickly with respect to the concrete (this being dependent mostly to solar radiation as opposed to air temperature) and so the membrane is initially extended while it is relatively cool. Conversely the crack narrows while the membrane is still relatively hot. The test method is suitable for accelerated testing of crack bridging and accommodating roofing membranes in hot sub-tropical climates. The test should only be used as a means of comparison and not as a test to predict actual performance behaviour. For a designated crack movement only a few months of summer exposure is necessary to compare and evaluate the crack accommodating ability of different systems.

![Diagram](image)

**Figure 2.2.** Roof coating test apparatus, after Jaegermann and Puterman

Although Jaegermann and Puterman report that reproducible crack widths were possible this refers to similar exposure conditions. On days with differing amounts of sunlight differing crack widths will be experienced by the slab and membrane. This means that
because daily conditions may not be exactly duplicated only results obtained from tests run concurrently can be compared and not those from tests conducted on different days. It would be necessary to employ some form of controllable artificial weathering and a repeatable method of crack opening to allow comparison of non-concurrent tests. It may be possible to use the test piece described in some type of weatherometer which should allow both reproducible weathering and crack opening. No mention is made of the way that the crack in the coating is detected.

2.3.2. AFNOR T 30-702:1976

The test is performed on a substrate of blocks of cementitious mortar 60 x 150mm each, set in a wooden frame 300 x 540mm and then coated with a cement skim, Figure 2.3. The coating to be tested is applied at the rate specified by the manufacturer and allowed to dry. The test procedure involves subjecting the coating to the following sequence:

- 14 Hours of water spray at 20°C
- 2 Hours ultra-violet light exposure at 60°C
- 2 Hours at -20°C
- 2 Hours water spray at 20°C
- 2 Hours at -20°C
- 2 Hours ultra-violet light exposure at 60°C

This sequence is counted as two cycles. After 5 days of this exposure, i.e. at each weekend, the panel is kept at 20°C for two days. For the coating to fulfil the requirements of this test it must withstand 150 cycles of the above regime without cracking, blistering, flaking etc. This test is the basis of a guarantee system backed by insurance in France.

The test provides no means of exerting a specific movement, although a small amount of relative movement between blocks occurs. The crack is pre-formed in the substrate as it is made from several pieces. There is also no procedure for measuring the width of any cracks. Constraint from the coating being tested will mean that any relative movement
between blocks will depend on the mechanical properties of the coating as well as on the temperature variations throughout a test. This means that different coating materials will experience different strains and in that sense the results of tests on different coatings are not comparable. It should be noted that this test is not specifically a crack bridging or accommodating test but is meant to test the overall performance of a coating system.

2.3.3. Waterproofing concrete bridge decks: materials and methods

Transport and Road Research Laboratory (TRRL) Report 636, Macdonald, details several tests to evaluate the suitability of different systems for the waterproofing of concrete bridge decks. One of these tests is for crack bridging ability and is described below.

The waterproofing membrane must not fracture if existing cracks in the concrete bridge deck widen or if new cracks develop. The reinforcement in highway bridge decks is designed to limit cracks to a nominal 0.25mm. The membrane should be able to withstand fracture at the permitted crack width multiplied by factors of 1.2 to allow for widening of the crack under repetitive loading and 2.0 to allow for variability in the performance of the
waterproofing system and for crack widths of greater than 0.25mm. The system would have to be satisfactory at crack widths of up to 0.6mm.

The substrate used in the TRRL test is a reinforced concrete slab measuring 700x230x75mm with a crack inducer at its centre, Figure 2.4. The concrete is made from a gravel aggregate of 20mm maximum size and mix proportions of 1:2:3.5/0.6 by weight. The slabs are cured under polythene for 14 days and then allowed to dry for a further 14 days. The concrete should have a brushed finish with a maximum trough to peak height of 2mm. If a resinous, thin film material is going to be tested the sharp peaks must be removed with a steel straight edge. The system to be tested should be applied in the manner specified by the manufacturer. Adequate time for curing should be allowed. Testing may be carried out during the day after application with prefabricated materials fixed to the concrete with bituminous adhesive and not until after 7 days or until the curing period specified by the manufacturer has elapsed when testing spray or brush applied materials.
Tests are carried out by loading the slab in bending using a jack and a frame, Figure 2.5. The crack opening is measured by a dial gauge graduated to 0.01mm and mounted at the mid-point of the slab with its stylus axis level with and parallel to the coating system/concrete interface. The load is applied until the concrete cracks at which time the system over the crack is examined, with a microscope if necessary, and the position and extent of any damage is noted, along with the dial reading but excluding a 12mm strip along the edge of the system. The crack is now opened at a rate of 0.2mm per minute. The system is continually examined during the loading. The crack is held constant at 0.25mm for at least 30 minutes and subsequently at 0.6mm. If a pinhole or crack develops in the system the test is continued until one of the following conditions is fulfilled:

- a single fracture having an overall length of 12mm or more occurs or,
- several fractures having a total length of 25mm occur, or
- the crack opens to 2.5mm without either condition (i) or (ii) being fulfilled.

No allowance is made for the cyclic opening of the crack which means that the procedure cannot be used for testing the crack accommodating ability of a coating but only its crack
bridging ability. There is no mention of recommended test temperatures in the reported method although in a description of the testing carried out for the report -10°C and 20°C are mentioned. The procedure specifies that the crack width be measured on one side only but if the crack edges are not parallel this could not be seen with only one gauge and so an unreliable result would be obtained.

2.3.4. Building Research Establishment apparatus and procedure

The apparatus for this test can be shown in Figure 2.6. The test substrate is a block of 1:3 (cement:sand) mortar. It is cast in a steel mould with an insert across its base at the centre to reduce the section of the block and so act as a crack inducer. There are also inserts at the sides to allow the jaws of the test machine to grip the block. The jaws are movable by a lead screw in increments of 0.02mm. To prevent elastic recoil from opening the crack when the block is broken there is a steel plate adjustable by feeler gauges that limits the movement of the jaw until the crack has formed. The block, after coating as specified by the manufacture is set in the machine and the jaws are opened using the adjustable plate to limit the jaw movement. Fracture is indicated by a distinct click from the block. Whitely and Rothwell believe that it is important to form the crack in-situ, beneath the coating. The adjustable plate is now removed and the crack opened in suitable steps, for example, 0.1mm. This is continued until the film fractures at which point the crack width is noted. The result is expressed as the crack width at which failure occurs.

This apparatus would be difficult to operate at non-ambient temperature as it has to be operated manually. This would involve either a temperature controlled glove box or a room with a controlled environment. After crack formation the strain rate of the test is dependant upon the speed with which the lead screw is turned, and in any case will not be constant. Crack width is obtained from graduations on the lead screw and not directly from the sample. There is some free-play between the specimen and the apparatus which may lead to inconsistencies in the measurement of crack width.
2.3.5. Modelling of Glass Fibre Reinforced Resin Coatings on a Cracked Surface of Concrete

This test procedure was designed for the evaluation of glass fibre reinforced resin coatings used on the inside of concrete tanks susceptible to live cracks, containing liquids aggressive to concrete. The testing machine was designed and built at the University of Warsaw. The test substrate is two steel plates, 120mm x 40mm, that butt together and can slide in a frame. The plates of the test substrate are moved apart by the thermal expansion and contraction of a steel bar brought about by electric heating and air cooling. The plates can be moved at fixed speed and frequency. A microscope is used to examine the test piece. The variation of crack width with time, the force needed to move the plates and the temperature of the test piece are recorded automatically during the test. The testing sequence carried out is:

- at least 200 cycles with the crack opening from 0 - 0.1mm
- at least 150 cycles with the crack opening from 0.1 - 0.2mm
- at least 100 cycles with the crack opening from 0.2 - 0.3mm
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- at least 50 cycles with the crack opening from 0.3 - 0.4mm

This gives at least 500 cycles of testing, this number being related to the work of real tanks. Testing is carried out at a temperature of 30°C. After this regime of testing the crack was opened to 0.5mm for 1 week. Finally the crack was extended until the test piece was damaged. Failures usually occurred as a break in the coating, but sometimes as the surface treatment coming away from the substrate.

With this test, factors such as crack width and frequency can all be controlled although perhaps not independently. This test can be used to evaluate crack accommodating behaviour due to its cyclic nature. The substrate in this test is steel and not cementitious in nature which means that it does not model a concrete surface. It would have been more representative if concrete had been attached to the steel plate in some way. This would of course lead to a possible problem with concrete reproducibility. No mention of the method of detection of damage in the coating is made.

2.3.6. MOAT 24:1983, Crack bridging assessment

This standard contains various tests to assess the properties of plastic renderings. The one of interest here is Part 12, the Gap - bridging Test. The test substrate is made from three asbestos cement blocks 150x50x10mm with two bevelled edges, Figure 2.7. The blocks are clamped together to form a test substrate that has two cracks less than 0.1mm wide. The surface treatment under test is applied to the substrate as specified by the manufacturer. The coating is left to dry for one month at 23°C and 50%rh. When the test is to be carried out the clamp is removed and a wedge is driven between the blocks to force the crack open. A vice is recommended for this procedure. The cracks are gradually widened until the rendering fails. This is detected by the observation of a light shone from underneath the specimen. Five to ten measurements of crack width are taken at regular intervals during the test until the surface treatment fails. The upper and lower values between which the surface treatment fails are recorded. The conditions of the test are 23°C±2°C, 50% rh and at 0°C after three days at 0°C.
A vice is used to open the crack which means that the rate of opening is not constant. This makes it almost impossible to duplicate test conditions exactly. It seems that the detection of a failure is carried out using the naked eye. A failure at a smaller size may be detected in a dark coating than in a light coating due to the greater contrast of the dark coating with the light shone from underneath. This could lead to different results from different coloured coatings making comparison of results difficult. The test assesses crack bridging ability but as there is no mechanism for closing the crack it cannot assess crack accommodation ability. The crack is pre-formed in the substrate material as it is made up of more than one piece. This will model a pre-cracked coated system but not a system where the crack is formed in-situ beneath the coating.

![Diagram](image)

**Figure 2.7.** Front view of apparatus for MOAT 24 test

2.3.7. ASTM C 836-95: High solids content, cold liquid-applied elastomeric waterproofing membrane for use with separate wearing course

This standard test specification contains several test procedures including (i) Low temperature flexibility and crack bridging, part 4.7 and (ii) Extensibility after heat ageing, part 4.12
Low temperature flexibility and crack bridging, part 4.7

The test substrate is manufactured from a 2:1:0.7 (aggregate:cement:water) mortar. The blocks are cured at 100% humidity for one day and then under water for six days. Two of the blocks are bound together with masking tape as shown in Figure 2.8. The surface treatment is applied over the 50.8 x 50.8mm area bisected by the artificial crack to a depth of 1.52±0.13mm, as specified by the manufacturer, within 48 hours. The specimens are cured for fourteen days at standard conditions followed by seven days at 70±2°C in a hot air circulating oven. The tape is removed after curing and the specimens are loaded into a tensile testing machine conditioned at -26°C. The specimen is subjected to ten cycles of movement consisting of moving the blocks apart at a rate of 3.2mm per minute until there is a gap between them of 3.2mm and the closing the gap at the same rate. At the end of ten cycles the specimen is removed from the machine and the surface treatment is examined for cracking, loss of adhesion or any other type of failure.

Due to the cyclic nature of this test it can be used to assess the crack accommodating behaviour of the coating. No mention is made as to how the damage in the coating is detected. Crack opening rate and frequency can be monitored and controlled by the testing...
machine that the work is carried out in. In this case the crack is effectively pre-formed as the substrate is in two parts.

(ii) Extensibility after heat ageing, part 4.12

Although this test is not specified as a crack bridging test it does involve the bridging of a crack formed in-situ beneath the coating. The substrate is prepared from the same type of mortar in part 4.7 (above) but this time cast into slabs 457.2 x 152.4 x 76.2mm. Curing is carried out as before. The slabs are cut into 152.4 x 76.2 x 25.4mm using a diamond masonry saw. The cut surface is used for the tests. The slabs are then cut to a depth of 19mm across the centre of the 152.4mm face as shown in Figure 2.9. Bench marks are put on the 152.4 x 25.4mm face 50.8mm apart and 25.4mm either side of the slot. A 25.4mm strip is masked off along the ends of the largest face on the cut side.

The surface treatment is applied to a depth of 1.52±0.13mm within 48 hours, as specified by the manufacturer. The three specimens are allowed to cure for fourteen days at standard conditions. The test specimens are aged in a circulating air oven for a further fourteen days at 70±2°C. The specimens are allowed to cool for an hour at standard conditions and the
masking tape is removed. The test specimens are now placed surface treatment down on a polythene covered wooden board and the ends of the specimen are restrained by wooden blocks nailed to the board. A steel wedge is inserted into the slot and hit with a hammer hard enough to crack the block.

As in the test for Low temperature flexibility and crack bridging the strain rate for this test is known. It is used for assessing crack bridging after heat ageing. As in other tests where the crack is formed in-situ below the coating the initial strain rate of the coating at the time of crack formation is not known. It does however model cracks formed in-situ beneath the coating.

2.3.8. University of Dortmund: Crack accommodation assessment

A method described by Englefried uses a substrate of a standard re-profiling mortar to give a reproducible substrate, Figure 2.10. The surface treatment under test is applied to this "coating carrier". The assembly is enclosed in a climatic cabinet to allow testing at different temperatures. Load is applied vertically to give a horizontal movement of the substrate. The crack is opened and closed by this loading which may be varied in both magnitude and frequency to vary crack width and crack opening frequency respectively. Aged surface treatments are subjected to this crack movement at various temperatures in the range of -20°C to 20°C. The result of the test is expressed as the number of cycles at which the coating fails.

The reference says that the crack is synthetically formed but does not go into any detail. It is possible that the steel plates to which the coating carrier is applied are bent or extended to form the crack but whether this is done before or after application of the coating is also not clear. Examination of the coating surface is carried out with an endoscope to allow observations without the need to open the temperature chamber. The substrate is not really a representative surface (being a repair mortar) on which to carry out this test although it is easy to reproduce.
2.3.9. Institut fur Bauforschung: Crack accommodation assessment

This test procedure incorporates a mortar prism to act as the substrate, Schwamborn. The prism is cast around a steel bar which acts as a closing spring during the cyclic testing. The prism is 40 x 40 x 160mm, Figure 2.11. The mortar is made from portland cement to DIN 1164, and quartz sand with a grain size of 0-2mm. The water/cement ratio is 0.50. The steel bar is 8mm diameter pre-stressing steel (1420/1570 N/mm²) and 800mm long. The centre portion of the bar is covered with a 90mm length of plastic tubing to stop stress transfer from the steel to the mortar. The prism is cured in water for 7 days after which it is stored at 23°C and 50% rh. After 21 days one surface of the prism is given a light sandblasting. A slot is cut in the face opposite to the one that was sandblasted to a depth of 16mm (to miss the bar) to act as a crack inducer. The surface treatment is applied to the sandblasted face of the prism. The prism is the weathered in a purpose built machine using the following sequence:

- water spray 18 minutes
- dry period (60-80% rh) 102 minutes
The weathering lasts for 2525 hours which is about 105 days. The ultra-violet light is provided by xenon arc lamps (compared with the QUV Weatherometer which uses fluorescent tubes). The process of fatigue testing of the surface treatment is carried out by loading the prism in tension by means of the steel pre-stressing bar. This is done with an INSTRON 8034 servo-hydraulic fatigue machine. Testing is carried out in a climatic cabinet at a temperature of -20°C. An extensometer, with an accuracy of at least 0.001mm is attached to one side of the specimen to monitor crack width and to control the fatigue machine. This test procedure simulates both temperature and traffic induced crack movements. Temperature induced crack movements are represented by a cyclic loading at a frequency of 0.03Hz. To represent traffic loading a cyclic loading at 5Hz is superimposed onto the 0.03Hz loading as shown in Figure 2.12.

A complete fatigue test is 1000 cycles which takes 9.23 hours. If the surface treatment is still intact after 1000 cycles the temperature is raised to 23°C and the crack is opened to a predetermined value and fixed by gluing a steel plate across each side of the crack. The
prism is then held at 70°C for seven days. The surface treatment is now examined visually for cracking and delamination. The requirements for a successful crack bridging test are that no cracking or delamination occurs after completion of both the fatigue and the static parts of the test. The surface treatment is classified by the magnitudes of both the fatigue and static displacements used. These classifications are shown in Table 2.3.

![Figure 2.12. Crack opening waveforms to simulate crack opening due to thermal expansion and contraction and traffic movement](image)

Although an extensometer with an accuracy of 0.001mm was used to monitor and control the crack width it was only reading the crack width at one end of the crack. If the crack were to open more at one end than the other the crack could actually be narrower or wider than the values to which it is being controlled. It would have been more thorough to measure the crack width at both ends to see if the crack is tapered and if so to what extent. This tapering of the crack could be brought about by several factors. If the reinforcing bar was bent it would try to straighten as the load was applied. Misalignment of the specimen in the machine could also cause this to happen. It is not clear if when the surface of the sample is examined visually it means with the naked eye or with a microscope.
Table 2.3 Material classification after testing.
(Where, \( w \) is the crack opening range, \( f \) is the crack opening frequency, and \( c \) is the test duration in cycles. The subscript \( tr \) indicates thermal loading, \( si \) indicates traffic loading and \( st \) indicates static loading.)

2.3.10. Swamy: Crack accommodation assessment

The test procedure described by *Swamy* details both a crack bridging and crack accommodate evaluation. The coating under test was an acrylic rubber type applied to a thickness of about 1000\( \mu \)m. The static test uses a substrate of slate board 150 x 250 x 5mm. The area coated measured 100 x 200mm. The surface treatment thickness was varied and the results
expressed as a graph of crack width against surface treatment thickness. Results were also obtained of elongation and tensile strength with temperature.

The dynamic test used a coating thickness of 1000μm. Crack width and temperature were varied. The testing sequence is listed below:

Step 1, total 2001 cycles

667 cycles at 20°C, then 5°C, and finally -10°C

with the crack width varying from 0.5 to 1.0mm

Step 2, total 4002 cycles

667 cycles at 20°C, then 5°C, and finally -10°C

with the crack width varying from 1.0 to 2.0mm

Step 3, total 6003 cycles

667 cycles at 20°C, then 5°C, and finally -10°C

with the crack width varying from 2.0 to 5.0mm

The surface coating is examined at the end of each 667 cycles and finally at the end of 6003 cycles. Any damage is recorded. The surface treatment fails the test if there is a complete break through the coating.

This test was reported in the reference testing specific commercially available coating and the temperatures and crack widths and indeed the number of cycles of testing may be designed to aid the market perception of the coating. However, cycling a coating over a crack varying in width between 2mm and 5mm at -10°C is severe compared with other testing regimes reviewed here. The frequency and waveform used in the fatigue tests were not reported. There was no mention of how the damage to the coating was detected, that is whether an optical system or the naked eye was used.
2.3.11. Summary of existing test methods

All of the test methods described in the last section deform the coating under test in some form or another. The differences between the methods are the magnitude of the deformation, how it is applied, the rate at which it is applied, whether the specimens are aged and whether the test is an evaluation of crack bridging or crack accommodating behaviour. These parameters are detailed in Table 2.4. The deformation applied to the specimen ranges from the AFNOR test, Section 2.3.2, where it is completely un-defined and probably quite difficult to model as it relies on the relative (thermally induced) movement between adjacent mortar blocks to that of the Institut fur Bauforschung test, Section 2.3.9., where it is precisely defined and controlled by a servo-hydraulic fatigue machine. Crack opening rates vary from \(5.09 \times 10^{-6}\) mm/s to \(5.53 \times 10^{-3}\) mm/s and crack opening displacement values vary between 0.05 mm and 57.2 mm. Some test methods use no ageing, one uses natural exposure to the sun which increases as the test proceeds, some use artificial light from UV fluorescent tubes or xenon arc lamps and one uses heat ageing. Substrates vary from cementitious in nature to steel. Test temperatures range from -26°C to 60°C. This shows the great variation in conditions that are used to assess coatings. This may be due to the fact that the coatings are being assessed for different purposes. For example, the *Klosinski* test is used to assess coatings for liquid filled tanks and the *Jaegermann and Puterman* test is used to assess coatings for roofs.

2.4. Requirements for a Coating Evaluation Test

It seems most likely that for general use, if a coating is going to be subjected to cracking in its substrate concrete, then that crack is likely to be active. This activity could be high frequency/low level loading or low frequency/high level loading. High frequency/low level loading could be caused by traffic moving across a bridge. This loading would vary depending upon the weight and configuration of vehicles involved, their speed and their spacing. Low frequency/high level loading could be caused by thermal cycling of the structure due to parts being heated by solar radiation and parts remaining in the shade. A test procedure must be able to evaluate crack accommodating as well as crack bridging
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(defined in Section 2.2.1) behaviour. Given that the structure is likely to be subjected to high frequency/low level and low frequency/high level loading, a test procedure must be able to test under conditions that allow the crack width and crack opening frequency to be varied.

<table>
<thead>
<tr>
<th>Test</th>
<th>Opening Rate (mm/s)</th>
<th>Opening Width (mm)</th>
<th>Opening Range (mm)</th>
<th>Cyclic Ageing/Weathering</th>
<th>Substrate</th>
<th>Temperature (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jaegermann</td>
<td>50.9x10^-6</td>
<td>0.6</td>
<td>0.1 - 0.7</td>
<td>Yes</td>
<td>Sunlight</td>
<td>Concrete 22°C to 45°C</td>
</tr>
<tr>
<td>TRRL</td>
<td>3.33x10^-3</td>
<td>0.6</td>
<td>0 - 0.6</td>
<td>No</td>
<td>n/s</td>
<td>Concrete n/s</td>
</tr>
<tr>
<td>BRE</td>
<td>27.8x10^-3 to 55.5x10^-3</td>
<td>To failure</td>
<td>To failure</td>
<td>No</td>
<td>n/s</td>
<td>Mortar n/s</td>
</tr>
<tr>
<td>ASTM-LT</td>
<td>0.89x10^-3</td>
<td>3.2</td>
<td>0 - 3.2</td>
<td>Yes</td>
<td>n/s</td>
<td>Mortar -26°C</td>
</tr>
<tr>
<td>ASTM-HA</td>
<td>0.2</td>
<td>57.2</td>
<td>0 - 57.2</td>
<td>No</td>
<td>Heat</td>
<td>Mortar Standard</td>
</tr>
<tr>
<td>Schwamborn</td>
<td>0.008</td>
<td>0.05</td>
<td>0.1 - 0.15</td>
<td>Yes</td>
<td>Xenon arc+ water</td>
<td>Mortar -20°C</td>
</tr>
<tr>
<td></td>
<td>0.03</td>
<td>0.2</td>
<td>0.1 - 0.3</td>
<td>Yes</td>
<td>n/s</td>
<td>Mortar n/s</td>
</tr>
<tr>
<td></td>
<td>0.03</td>
<td>0.2</td>
<td>0.2 - 0.4</td>
<td>Yes</td>
<td>n/s</td>
<td>Mortar 20°C to 60°C</td>
</tr>
<tr>
<td>AFNOR</td>
<td>n/s</td>
<td>n/s</td>
<td>n/s</td>
<td>Yes</td>
<td>uv+ water</td>
<td>Mortar n/s</td>
</tr>
<tr>
<td>Klosinski</td>
<td>0</td>
<td>0.1</td>
<td>0.1</td>
<td>Yes</td>
<td>n/s</td>
<td>STEEL n/s</td>
</tr>
<tr>
<td></td>
<td>0.1 - 0.2</td>
<td>0.1</td>
<td>0.1</td>
<td>Yes</td>
<td>n/s</td>
<td>STEEL n/s</td>
</tr>
<tr>
<td></td>
<td>0.2 - 0.3</td>
<td>0.1</td>
<td>0.1</td>
<td>Yes</td>
<td>n/s</td>
<td>STEEL n/s</td>
</tr>
<tr>
<td></td>
<td>0.3 - 0.4</td>
<td>0.1</td>
<td>0.1</td>
<td>Yes</td>
<td>n/s</td>
<td>STEEL n/s</td>
</tr>
<tr>
<td></td>
<td>0.4 - 0.5</td>
<td>0.1</td>
<td>0.1</td>
<td>No</td>
<td>n/s</td>
<td>STEEL n/s</td>
</tr>
<tr>
<td>MOAT 24</td>
<td>n/s</td>
<td>To failure</td>
<td>To failure</td>
<td>No</td>
<td>n/s</td>
<td>Asbestos cement RT</td>
</tr>
<tr>
<td>Englefried</td>
<td>n/s</td>
<td>n/s</td>
<td>n/s</td>
<td>Yes</td>
<td>n/s</td>
<td>Repair mortar 20°C</td>
</tr>
</tbody>
</table>

Table 2.4 Summary of various test methods for the evaluation of crack bridging and crack accommodating behaviour of coatings.

where: n/s = not specified and uv = ultra-violet light

The crack has the possibility of forming either before the coating is applied or after coating application. If the crack forms before the coating is applied, for example coating an old structure, the coating material may penetrate the crack to some extent. This is clearly different to coating a structure that has no cracks, for example a new structure, as the crack would now be formed in-situ, beneath the coating. A test procedure should be capable of testing a specimen with both of these starting conditions, substrate un-cracked or cracked before coating application.

Under in-service conditions a coating will be subjected to extremes of temperature and varying degrees of exposure to ultra-violet radiation and moisture. It is well known that temperature can alter the modulus of a polymer by several orders of magnitude depending upon which side of the glass transition the measurement was made. A test procedure should allow evaluations to be carried out at various temperatures representative of the in-service conditions to which the coating will be subjected.
Another well known phenomenon is the degradation of polymers that is caused by exposure to ultra-violet radiation. A procedure should be used to allow the coating to be subjected to moisture and ultra-violet radiation so that it can be weathered artificially. Given that artificial weathering normally takes several hundred hours to complete, this could not be carried out during a crack accommodation test and would have to be carried out separately. In addition, there are standard test machines for artificial weathering that allow reproducible conditions to be attained. An example is the QUV Weatherometer described in *ASTM G53-95* which allows control over exposure to ultra violet radiation, temperature and moisture.

All of the procedures described in Section 2.3 meet at least two of these criteria although the method of application varies between tests. For example Section 2.3.1, where the test procedure for the evaluation of roof coatings in Israel is described, uses a cyclic crack opening with varying temperature and weathering (although in this case it is real and not artificial). In contrast, Section 2.3.3, the procedure for the evaluation of waterproofing materials for concrete bridge decks is a crack bridging only test that uses two temperatures, no cycling of the crack width and no weathering.

In reviewing these methods it can be concluded that the test procedure for the evaluation of coating materials, as defined in Section 2.2, must include the following features:

- crack bridging test, quasi-static
- crack accommodating test, cyclic variation of the crack width, fatigue
- testing at various temperatures

In addition, it is desirable to evaluate the affect of weathering on the results obtained from the testing to the requirements just described.

Regardless of the specific procedure adopted however there is an overall requirement that it be reliably reproduced allowing results of subsequent tests to be compared.
2.5. Properties of Polymeric Materials

Protective coatings are used in places where they may be subjected to moisture, ultra violet radiation and extremes of temperature. Polymeric materials undergo a marked change in physical properties with a change in temperature. Generally speaking as an un-crosslinked, amorphous polymer is cooled it will change from a flexible material to a brittle material. This transition occurs over a range of temperature and is called the glass transition. The change in physical properties around the glass transition is caused by changes in molecular mobility.

2.5.1. The Glass Transition

'A linear polymer chain can be treated as a one dimensional co-operative system in which the rotation of a chain segment is restricted or aided by the neighbouring segments', Cowie. Any significant movement is governed by the ease with which a chain segment can move between one rotational state and another. At temperatures below the glass transition large scale molecular motion is effectively frozen out as there is insufficient thermal energy to allow rotation of chain segments. Small groups of atoms still vibrate about their equilibrium positions but this is only on a local scale, Billmeyer, and so this does not allow large scale chain movement. Above the glass transition region there is sufficient thermal energy to overcome the energy barrier to segmental rotation and so large scale co-operative molecular movement is able to take place. This leads to rubbery behaviour. If the polymer is un-crosslinked and the temperature is raised further it behaves like a viscous liquid. If it is crosslinked there is still some restraint operating upon the chains and this restricts their maximum movement. This stops the polymer from behaving like a viscous liquid at increased temperature.

2.5.2. Detecting the glass transition

As this transition has such a significant affect on the properties of the polymers from which the coatings are formulated it is important to be able to know over what temperature range it will occur. Techniques for locating the glass transition temperature can be divided into two
categories, static and dynamic. In the static methods changes in the temperature dependance of an intrinsic property such as heat capacity or density are followed. The sample must be allowed to equilibrate and relax at each temperature before measurements are taken. With the dynamic methods a rapid change in modulus or a peak in mechanical damping indicates the glass transition. It must be noted however that the glass transition temperature is dependant on the frequency of the applied force. This is due to restrictions on molecular motion in the polymer. Glass transition temperature has been shown to increase by 5K - 7K for a decade increase in the frequency of the applied force.

2.5.3. Viscoelasticity

A material subjected to deformation may respond in a variety of ways. An applied stress may lead to an immediate elastic strain, an elastic response. It may lead to a strain that increases with time, a viscous response. There may also be a combination of these responses, a viscoelastic response. Examples of the viscoelastic response are Creep, which is seen as a delayed strain response to an applied stress; Stress Relaxation, which is seen as the reduction in stress after the application of a strain and a Dynamic response where the strain varies at the same frequency as the applied stress but out of phase with it. An artefact of this dynamic response will be used in Section 3.8 in the technique to find the glass transition temperature of the coating materials investigated during this work.

It is necessary to be able to describe the viscoelastic response in more detail. An idealised model of this response is described below. Upon the application of a stress a polymer will respond in a number of ways. These are illustrated in Figure 2.13, Cowie and Billmeyer. Region (a) shows the elastic response. In this region the strain is related to the applied stress by the Young's Modulus of the material. Regions (b) and (c) show the creep response. The material creeps quickly at first, region (b), which is recoverable creep. The rate of creep slows and eventually becomes constant. This constant section, region (c) is viscous flow. When the stress is removed the elastic strain is immediately recovered, region (a'). The creep that took place in region (b) is slowly recovered in region (b').
However, there is a shortfall in the recovery, region (c'), and this is due to the viscous flow that took place in region (c). This viscous flow is completely non-recoverable.

This idealised model can be described by a combination of idealised mechanical elements. The elastic response is represented by a spring. The spring is an ideal elastic element and conforms to Hooke's law. The stress ($\sigma$)/strain ($\gamma$) response of the spring with a modulus $G$ is instantaneous and independent of time. It can be described by Equation 2.7:

$$\gamma = \frac{\sigma}{G}$$  \hspace{1cm} 2.7

This response is shown in Figure 2.14. The spring is a system that stores energy which is recoverable. The response of a viscous material is represented by a dashpot. The dashpot is an ideal viscous element and demonstrates the response of a Newtonian fluid. The response is linear with time and is non-recoverable as energy is dissipated by the dashpot. If the dashpot has a viscosity $\eta$ its response is described by Equation 2.8:

$$\frac{d\gamma}{dt} = \frac{\sigma}{\eta}$$  \hspace{1cm} 2.8
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Figure 2.14. The stress/strain response of a spring

Figure 2.15. The stress/strain response of a dashpot
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The dashpot represents the retarded nature of a material and its stress ($\sigma$)/strain ($\gamma$) response can be seen in Figure 2.15. If these two elements are combined in series they form a Maxwell element and the assumption is made that the strains on the spring and dashpot are additive. When the stress is applied the spring immediately elongates and the dashpot slowly yields. When the stress is removed the spring recovers but the dashpot does not. The strain on the Maxwell element can be written as Equation 2.9:

$$\frac{d\gamma}{dt} = \sigma/\eta + (1/G) d\sigma/dt$$  \hspace{1cm} 2.9

When shear strain rate does not change this becomes:

$$\frac{d\sigma}{dt} + G \frac{\sigma}{\eta} = 0$$  \hspace{1cm} 2.10

Assuming that at zero time $\sigma=\sigma_0$ this becomes:

$$\sigma = \sigma_0 \exp(-tG/\eta)$$  \hspace{1cm} 2.11

where $\sigma_0$ is the stress immediately after the polymer is deformed. This shows that if a Maxwell element is held at a fixed shear strain the stress on it will relax exponentially. At time $t=(\eta/G)$ the stress is reduced to $1/e$ times its original value and this time is known as the relaxation time $\tau$. The stress/strain response for the Maxwell element is shown in Figure 2.16.

If the spring and dashpot are combined in parallel the deformation on each is the same. This is the Voigt-Kelvin element. This element shows a retarded elastic or viscoelastic response where the dashpot retards the spring in reaching equilibrium, Figure 2.17. The stress/strain response is described by Equation 2.12.

$$\eta d\gamma/dt + G\gamma = \sigma$$  \hspace{1cm} 2.12

If the stress is later removed the response is given by:

$$\gamma = \sigma/G (1 - \exp^{-(G/\eta)t})$$  \hspace{1cm} 2.13
which is:

\[\gamma = \sigma J (1 - \exp^{-t/\tau})\]  \hspace{1cm} 2.14

where \(J\) is the elastic compliance \((1/G)\). When the stress is removed the spring returns to its original state with the response:

\[\gamma = \gamma_0 \exp^{-t/\tau}\]  \hspace{1cm} 2.15

The idealised model of the creep behaviour can be represented by a Maxwell and a Voigt-Kelvin element in series, Figure 2.18. Figure 2.13 can be explained using this combination of elements. Figure 2.18 (a) shows the system at rest before any stress has been applied. The stress is first applied to spring \(E_1\) and dashpot \(\eta_3\). Figure 2.18(b) represents zero time when the stress is applied. This leads to an extension of \(E_1\) \((\sigma/E_1)\) which corresponds to region (a) in Figure 2.13. Now there is a decreasing rate of creep and the stress on \(E_2\) increases until none is carried by \(\eta_2\) at which point \(E_2\) is fully extended, Figure 2.18(c). This is region (b) in Figure 2.13. The creep is now occurring at a constant rate due to the deformation of dashpot \(\eta_3\). Region (c) is described by dashpot \(\eta_3\). This dashpot continues to deform until the stress is removed. When the stress is removed \(E_1\) recovers its strain immediately, region (a') Figure 2.13 and Figure 2.18(d). The spring \(E_2\) is also forcing dashpot \(\eta_2\) to recover and this is described by region (b'). There is however no restoring force on dashpot \(\eta_3\) and so it remains in its extended state. This is described by region (c') and shown in Figure 2.18(e).
Figure 2.16. The stress/strain response of the Maxwell element

Figure 2.17. The stress/strain response of the Voigt-Kelvin element
Figure 2.18. A simple model of viscoelastic behaviour.
2.5.4. Degradation of polymers

Protective coatings used on reinforced concrete will be exposed to ultraviolet radiation, air and water borne pollutants and extremes of temperature, due to the fact that the majority of these structures will be outdoors and therefore exposed themselves. All of these factors may effect the durability of the system to some extent. It is therefore important to have an understanding of these degradation processes and their effect on durability and future maintenance. The financial implications of closing a structure to the public, erecting scaffolding and re-coating are important factors when specifying a coating system. Harwood states ‘weathering from ultraviolet light, changes in humidity and temperature will deteriorate the binder in the surface coating and reduce the resistance to thermal stresses and reduce progressively the dry film thickness of the coating’. Ultra violet light, water and oxygen in the atmosphere attack paint films causing the polymer molecules to break up into smaller fragments, Turner. The surface becomes dull and powdery and when it is in this condition it is said to have chalked. The powdery material is easily removed and the resulting reduction in thickness leads to a reduction in the barrier properties of the coating and so it may no longer perform as it was required. Chalking can be reduced by keeping the pigment volume concentration as low as possible. If the pigment volume concentration is high it will only take a small amount of the polymer binder to degrade in order to cause the detachment of the surface pigment particles. Clearly then, some form of protection against weathering should be incorporated into the coating system. Verbanc states that unprotected polymer degrades at ambient temperatures in sunlight leading to crazing of the polymer surface which can quickly become serious enough to destroy its usefulness. It can be protected from ultra violet light catalysed oxidation by the incorporation of carbon black or highly coloured ultra violet stable pigments. Pigments that bleach lose their effectiveness. In addition to losing their effectiveness as protection for the polymer binder of the coating, a pigment that is not stable will cause the appearance of the coated surface to change. This may prove to be aesthetically un-acceptable.
In order to reduce the susceptibility to weathering the mechanisms involved should be examined. There are two types of polymer degradation process and they roughly correspond to step reaction polymerisation and chain reaction polymerisation. Random degradation can be compared to the reverse of step polymerisation, Billmeyer. Chain scission occurs at random points along the chain leaving fragments that are usually large compared to a monomer unit. Polyethylene exhibits this type of degradation, Ashby and Jones. Chain de-polymerisation leads to the release of monomer units from a chain end which is essentially the reverse of chain polymerisation. Polymethylmethacrylate behaves in this manner. These processes may occur separately or in combination. They may be initiated by heat, ultra violet light, oxygen, ozone or some other foreign agent.

In addition to weathering there are other processes that can cause the integrity of a protective coating to be compromised. These involve the reduction or loss of bond strength between the protective coating and the concrete substrate.

Polymer coatings on concrete surfaces repeatedly exhibit cracks, blisters or delaminations. Osmotic and capillary pressure have been investigated by Gunter and Hilsdorf. Pressures of up to 4.5MPa and 0.2MPa in the case of osmotic and capillary pressure respectively have been found acting on the interface between the concrete and coating. The initial moisture content of the concrete was shown only to effect the development of capillary pressure however, the pressures after prolonged exposure are independent of the initial moisture content. This is probably due to the moisture content of the concrete reaching a similar level irrespective of the initial value (oven dried, 65% r.h. and 80% r.h.). This suggests that the initial moisture content is not critical as it does not effect the long term durability of the coating with respect to capillary pressure. This reduces perpetration time and hence application costs. However, it has been suggested by Bundies that the moisture content of the surface of a concrete structure is important when applying a typical epoxy primer from a two component coating system in that it only takes 10% water to disturb the stoichiometric reaction between the epoxy and hardener. These primers are used to overcome the problems of applying a coating to a surface that is both highly alkaline and rough in nature. Local defects are also listed as a possible cause of debonding of the
coating when the pressures at the interface are less than that required to cause debonding.

Taking a penny shaped defect as an example, the edges of the defect will cause a stress concentration of the form of a 'crack tip'. This stress concentration will allow pressures in the defect to cause failure of the coating/substrate bond that would not normally cause failure where no defect was present. Hewlett also suggests that capillary pressure beneath a coating can cause failure of the bond. In addition he points out that dissolved salts may penetrate through the coating and crystallise, at the concrete/coating interface causing bond failure. This often occurs where one side of the concrete is wet, for example a wall supporting an earth bank.
3. Details of experimental procedures

The requirements for both the crack bridging/accommodating specimen and the testing machine were arrived at from the review of existing test methods and the conditions of service to which the coating would be subjected. This has been discussed in Chapter 2. We now need to develop a test method and a specimen along with its associated testing machine. Specimen requirements and design are discussed in Section 3.1 and the requirements and design of the testing machine are discussed in Section 3.2

3.1. Specimen design and manufacture

This section describes the properties that were required from the test specimen and how they were arrived at. The manufacture and preparation of the specimen are then described.

3.1.1. Specimen requirements

There were two main requirements to which the fatigue test specimen had to comply.

- That it would model as closely as possible a crack in a reinforced concrete structure, both during crack formation and subsequent crack movement to enable testing of specimens coated both pre- and post-cracking.

- That the crack could be made to open and close repeatedly in a controlled manner so that the coating over the crack could be tested in fatigue (as happens in a real structure due to mechanical and thermal loading).

It was decided to use a test specimen similar to one used described by Herold and Schwamborn and Fiebrich. The overall configuration was considered to be suitable for this test for the following reasons.

- The specimen was considered to be long enough such that when the coating was applied to it by brush the region where the crack would form would be at the centre of the brush stroke. This would lead to the thickness of the coating being
more constant than if at either end of the stroke when brush pressure is increasing or decreasing as the brush was lowered or raised.

- The specimen was considered wide enough such that any edge effects, for example possible differences in coating constraint between the edges and the centre region, would not influence the majority of the coating.

- The central reinforcing bar would provide a closing force for the crack and would also keep the two edges of the crack aligned.

To summarise, it was thought that the specimen would allow consistent results to be obtained, during both manufacture and subsequent testing. It should be borne in mind that the fatigue specimen is loaded off-axis, and if a thicker coating of high modulus is tested significant bending in the reinforcing bar could occur which could lead to bending in the coating.

It was found on preliminary work that the bond between the reinforcing bar and the mortar was insufficient to give a reliable specimen and in some cases the mortar prism came away from the bars. To solve this problem epoxy resin was applied to the bar to give an increased surface roughness in the bond area. This is described in Section 3.1.2. End caps were also added to increase the strength of the reinforcing bar/mortar bond and this is described in Section 3.1.6. One further modification to the Herold configuration was the addition of another crack inducer in the form of a hole through the prism, again described in Section 3.1.6. This further reduced the section of the prism where crack formation was to take place and so allowed the crack to be initiated at a lower load and in fewer cycles. In addition there was a reduced chance that the mortar/reinforcing bar bond would fail in this shorter initiation period.

This specimen configuration has some properties that should be taken into account when it is being used. The crack will not be able to completely close due to friction between the reinforcing bar and the mortar and the rough edges of the crack not fitting perfectly together. This means that it will not be possible to perform a test where the minimum required crack opening is zero. The reinforcing bar must be plastically deformed to set the minimum crack opening. This means that the minimum crack opening must be lower than
the ultimate tensile strain of the bar. The crack opening required for the test must be such that it is lower than the elastic strain capacity of the bar at the plastic strain already imposed on the bar. Fatigue failure of the bar may become a problem when a large crack opening is required.

3.1.2. Description of fatigue test specimen

The fatigue test specimen is a mortar prism 40x40x160mm, Figure 3.1. The prism was cast around a steel reinforcing bar. This bar acts both as a spring to close the crack and to keep the two parts of the prism in alignment. The bar was 7.94mm (5/16 inch) in diameter and is made from freecutting steel (EN1A). The bars had epoxy resin applied to them as shown in Figure 3.2 to increase the shear strength of the steel/mortar interface. The specimen mould, Figure 3.3, was made from steel plate and is held together by 2 BA steel screws.

![Figure 3.1. Fatigue test specimen.](image)
Figure 3.2. Reinforcing bar showing position of epoxy resin.

Figure 3.3. Specimen mould.
3.1.3. Mortar

The first requirement, Section 3.1.1, means that a cementitious substrate is required. A 3:1 (sand:cement) mortar was chosen. The sand used was that fraction of Thames Valley aggregate that passes through a 5mm sieve. The cement used was Ordinary Portland Cement (OPC), made by Blue Circle. The water content of the mortar was 0.46 of the weight of the OPC. The sand was pre-dried in an oven at 105°C for 6 hours. At the start of this work sufficient sand and OPC were stored so that all mortar would be made using the same materials. After cooling 1.4% water by weight of sand was added to bring it to the saturated surface dry condition. This mixture was stored in an airtight container for 24 hours before mixing took place. The mortar was mixed in a pan type mixer with a driven pan. The pan and blades were dampened with a water soaked rag prior to mixing to reduce the amount of water lost from the sand to the mixer surfaces. The mortar was mixed for 3 minutes. It is very important to keep the mix proportions and the mixing time the same across batches as a change in either of these parameters will effect the workability and final strength of the mortar.

3.1.4. Mould preparation and casting

Due to the need to apply a coating to the specimen surface it was not possible to use a conventional mould release oil on the base of the mould as this would contaminate the specimen surface and interfere with the adhesion of the coating. The same is true of silicon release agents. It was found that not using a release agent led to the mortar bonding to the mould cavity, leading to the destruction of the specimen when it was removed from the mould. To overcome the problem it was decided to use a bleed ply to act as the mould release agent. The bleed ply, made by Tygovac, is used in the polymer composites industry. It is a glass fibre mat that has been treated with a Teflon release agent. The mat is not smooth and gives the specimen a surface texture which is reproducible. The surface texture from a steel mould is variable due to the water which becomes trapped in contact with it. The bleed ply also allows entrapped air to escape and so reduces the number of voids that form on the surface when compared with a conventional release agent. The
remaining faces of the mould are treated with Rocol RS7, a dry film mould release agent
supplied in an aerosol.

Any mortar remaining in the moulds from previous castings was removed by scraping,
wire brushing or bead blasting as necessary. A piece of bleed ply was then fixed to the
base of the mould using 3M Spray Mount adhesive. Thin strips were cut out of the bleed
ply to allow the mould partitions to sit properly in their slots. The partitions, side and end-
pieces were treated with Rocol RS7. One of the long side pieces was then screwed to the
base of the mould and the reinforcing bars fed through the holes up to the epoxy resin bond
ehancer. The other long side piece was passed over the bars and screwed to the base.
The bars were then clamped in place using the clamping screws. After the end pieces were
screwed in place the mould was complete and ready for the mortar to be cast.

3.1.5. Mortar casting and curing

The prepared mould was placed on the vibrating table and filled with mortar to a level
slightly above the reinforcing bars. The table was activated and allowed to vibrate until the
rate of evolution of bubbles from the mortar was much reduced. The mould was then filled
and vibrated again. As the level of mortar fell it was topped up. Vibration was halted when
the mould was full and large numbers of bubbles no longer appeared at the mortar surface.
The exposed mortar surface was finished with a steel float. The filled mould was then
placed in an environment of 100% humidity at 20°C for 24 hours after which the mould
was removed. The specimens were cured under water at 20°C for a further 6 days in a
curing tank.

3.1.6. Final preparation and coating

When removed from the curing tank the crack inducer slots were cut using a water cooled
and lubricated rotary diamond saw which cut a 3mm slot to a depth of 15mm. The
specimens were then washed under running water with a soft bristle brush to remove any
surface deposits from the curing tank and slotting operation and then left for 2 weeks in
laboratory air to dry.
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The next operation to be carried out was the drilling of the second crack inducer, the 6.35mm (0.25 inch) hole using a tungsten carbide tipped masonry twist drill. This operation had to be carried out slowly so as not to crack the mortar or to cause excessive heating. The specimen was then ready for the application of the surface coating. The coating system was applied in the proportions and thicknesses specified by the manufacturer. Where it was directed to brush on the primer the required amount was measured out and then brushed evenly over the specimen surface. Where flooding was directed the required amount of primer was poured evenly over the specimen surface. The coating material itself was brushed over the specimen surface to the wet film thickness specified by the manufacturer or calculated from the required dry film thickness and the volume solids data. Wet film thickness was measured in several places along the length of the specimen using a comb type gauge. The coating was left to cure in laboratory air for 2 weeks before testing took place.

The end faces of the coated fatigue specimen are abraded in a shot blasting cabinet with safti-grain 60/40 chill cast iron shot to remove any poorly adhered surface material. The reinforcing bars are abraded at the same time to a distance of approximately 15 mm from where they protrude from the end faces of the prism. Two end caps are also shot blasted and degreased. The abraded surfaces of the prism, reinforcing bars and end caps that will come into contact are coated with a two part, high strength epoxy resin system. The four bolts that hold the end caps together are treated with Rocol RS7 release agent in-case any epoxy resin gets into the threads. The end cap is slid onto the reinforcing bar and the two bolts are tightened evenly while holding the end caps into contact with the prism end face. The epoxy resin is allowed to cure for 24 hours before any further action is taken.

3.2. Description of the fatigue machine

The testing machine had to simulate as closely as possible the service conditions of a coating applied to an external structure. These requirements are listed below:

- cyclic test (tension-tension fatigue loading).
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- dedicated testing machine
- reliable power source.
- reliable and straightforward to operate, that is, no complicated operating procedures that could result in inconsistencies and errors.
- testing at a variety of temperatures.
- testing at a variety of frequencies.
- unattended operation.

When the design of the machine was initially considered with the above points in mind, a piston type linear actuator was decided upon. This would make the machine relatively straightforward to construct and operate. It gave the option of oil or air under pressure to operate the cylinder. The final choice was for a compressed air system. The reasons for this are:

- There was a possibility that the complete machine would have to be operated at low temperatures. Under these conditions the viscosity of oil can increase and alter the operating characteristics of the machine.

- Financial constraint. There was already access to a compressed air main in the laboratory which could be backed up with a portable compressor in the case of mains failure. In contrast the power pack for providing oil under pressure would be relatively expensive.

- Previous experience had demonstrated the feasibility of this approach.

The fatigue testing machine is described in this section. The construction and instrumentation of the testing machine are also described. A more detailed description of the design, construction and instrumentation can be found in Appendix A.

The machine comprises a pneumatic cylinder which loads the specimen via a lever. The cylinder position is controlled by a two position valve. This valve allows control of the
direction of travel of the cylinder. The valve is controlled by a timing controller. The heart of the timing controller is an asymmetric timing module. This module, in conjunction with the rest of the controller circuitry allows the frequency of the cylinder to be varied, and thus the load applied to the specimen. Additional controls to allow the cylinder to be held on either stroke were incorporated to make loading and un-loading of the specimen straightforward and to allow the crack to be held in the open position for examination. It was important for the cylinder to receive clean, oil bearing air to ensure reliability and this was accomplished with a filter/oiler unit. The filter blocked particles greater than 5 μm and also performed as a moisture trap. Load on the specimen was controlled by altering the pressure of the air being supplied to the cylinder. This was done with a regulator. The initial speed of the actuator was controlled in both directions. This allowed control of the loading and unloading rate. To accomplish this, variable flow restrictors were fitted to each end of the cylinder which modified the flow of the air being exhausted. Exhaust air was passed through one of two silencers to reduce disturbance caused to other laboratory users.

The specimen is held in the fabricated grips by pre-stressing collets and barrels. Temperature of the testing environment and hence the specimen is controlled by an Instron temperature cabinet using electric heating and liquid carbon dioxide cooling. Crack width is measured by a linear variable differential transformer (LVDT) fixed across each end of the crack. Data from the LVDT's is logged using a computer controlled data logger.

The loading assembly is mounted on a reaction frame which is itself mounted on a concrete plinth. The plinth provides vibration isolation from the surrounding environment and puts the machine at a suitable working height. A brace between the top of the reaction frame and the wall prevents the machine from oscillating about the web of the lower beam of the reaction frame.

The fatigue machine was built from scratch and as such most of the parts used in its fabrication were designed and built in-house. The main exceptions to this were the pneumatic hardware, the asymmetric timing module in the controller, the collet and barrels used in the grips and the temperature cabinet. The machine is shown in Figure 3.4.
Figure 3.4. Front view of the testing machine
3.2.1. Shape of waveform

The shape of the waveform controls the severity of the test and could take the form of a sine, square or triangular wave. A sine wave would be symmetrical and allow smooth application of load. A square wave would allow the crack width to be held at maximum or minimum values for a finite period of time. A triangular wave form would allow slower rise time than the square wave but there is no possibility to hold the load at maximum or minimum values. By considering the square and triangular waveforms it is possible to obtain the best features of both and produce a waveform which is trapezoidal in shape, Figure 3.5. This would allow a reasonably fast rise to peak crack opening (a-b), followed by a period where the crack is stationery (b-c), followed by the crack width falling to its minimum value (c-d) and finally a period when the crack is again stationary (d-a').

![Trapezoidal waveform](image)

Figure 3.5. Trapezoidal waveform

The rise (a-b) was set such that it gave the fastest rise in crack width consistent with reliable performance for the mortar/reinforcing bar interface and from the fatigue machine bearings. It was desired that the part of the wave form (a-c) would take approximately 1 second and
the part from (c-a') would take approximately 2 seconds. This would allow the material more
time to relax when the crack was at its minimum width than it had spent at the maximum

crack width.

In reality, the waveform that can be achieved by the apparatus is limited by using
compressed air to power the pneumatic cylinder. When the waveform was being set up it
was found that the fastest time (a-b) that complied with reliability of the specimen and
machine was 0.3 seconds. It was found however that the crack width was not steady at (b)
but continued to rise very slowly. This was due to friction in the bearings of the machine
and possibly between the mortar and steel of the specimen. This movement would continue
until the load in the load chain was equal to that being applied by the cylinder, as the air in
the cylinder would expand until this condition was met. It transpired that over the 0.6
seconds remaining of the period (a-c) this only led to an increase in crack width of 0.01
mm. This was only 2.5% of the crack movement and so this was taken as the stationery
period.

It was impractical to drive the cylinder in the opposite direction to close the crack as this led
to slack in the load chain which resulted in an impact as the slack was taken up at the
beginning of the next cycle. This impact was detrimental to both the apparatus and the
specimen causing damage to the machine bearings and to the specimen reinforcing
bar/mortar interface. However, if the air pressure was simply exhausted to atmosphere so
that both sides of the cylinder were at atmospheric pressure then the reinforcing bar would
pull the crack closed. This happens more slowly than the crack opening because as the
crack closed the restoring force in the bar was reduced and in addition friction in the
specimen, bearings and cylinder, had to be overcome. This damped crack closure took 1.5
seconds and a further stationery period of 1 second brought the total cycle period to the
desired 0.3 Hertz. The final wave chosen was thus not symmetrical but was reproducible,
Section 4.1.1, which was the requirement.

In designing the shape of the waveform to use in the test programme it was necessary to
keep the overall period of oscillation short to avoid autogenous heating of the coating
material. The overall period chosen was 0.3 Hertz which would allow a test of 6000 cycles to be carried out in 5.5 hours. Thus, making the assumption that crack opening due to thermal expansion happens once every day in a real structure, a crack accommodating test equivalent to 16.4 years of service can be carried out during one working day. Obviously, there will be variations to crack opening on a real structure in that the crack may open more or less often than once a day, or it may open to varying widths depending on the temperature and load. This means that it is impossible to equate the result of an accelerated test to an equivalent period in-service. The same problem is encountered when looking at artificial weathering.

In order for the test to be accelerated in nature the conditions to which the specimen is exposed must be exaggerated in some way, for example crack opening frequency, crack width and degradation due to weathering. The test is already accelerated as the frequency of crack movement is greater than would be found in a real structure. Another way of accelerating the test was to exaggerate the crack movement over that which would be found in a sound structure. The crack movement chosen was 0.3 mm. A crack width of 0.3mm being the limit imposed by BS:8110 during the design of reinforced concrete structures. However, this crack movement did not cause failures in commercial coatings. In addition it was known that once the crack had been initiated in the specimen it would never close up completely when the load was removed due to interference from the rough edges of the crack and also movements of the prism with respect to the reinforcing bar. In addition the minimum crack opening produced varied slightly from specimen to specimen. To achieve an accelerated test the crack movement of 0.3mm was superimposed over a minimum crack opening of 0.4mm by plastically deforming the reinforcing bar. The ability to do this was one of the constraints when selecting the pneumatic cylinder, Section 3.2. This minimum crack opening also removed the problem of variable minimum crack widths on crack formation.

During the development of the test it was found that if the reinforcing bar was plastically deformed to give a minimum crack opening of 0.4mm then it was still able to survive
repeated openings of 0.3mm giving a maximum opening of 0.7mm without failing in fatigue.

3.3. Principle of operation the machine.

The passage of compressed air around the machine is shown in Figure 3.6. Compressed air is supplied from the main and passed through a filter which removes particulate matter and moisture. The air then passes through the regulator where the required pressure is set and through a lubricator so that the valve and cylinder are lubricated internally. The oiled air passes into the inlet port 1 of the control valve. The valve is able to route the air to either of the ports on the cylinder depending on which solenoid is energised at that time by the timing circuit. If, for example, inlet port 1 is connected to outlet port 3, the piston will move downwards due to air pressure above the piston. This movement will force the air from beneath the piston through flow controller A and the exhaust valve. Depending upon the position of the exhaust valve the air will be exhausted straight to atmosphere (through ports a and b), or through ports a and c, and through the control valve ports 4 and 5 and finally through the silencer to atmosphere. If inlet port 1 of the control valve is connected instead to outlet port 4, two other outcomes are possible. When the exhaust valve is in such a position that ports a and c are connected air will be routed through the exhaust valve and flow controller A (which has no effect with flow in this direction) and into the cylinder beneath the piston. This will force the piston to move upwards. The air above the piston will be forced through the control valve, (ports 3 and 2), through flow controller B and finally to atmosphere through the silencer. However, if the exhaust valve is in such a position that ports a and b are connected, the base of the cylinder is isolated from the control valve and there is no air flow to the cylinder. This means that no movement of the piston will occur other than that caused by the elastic energy in the specimen reinforcing bar pulling the grips towards each other.

In order to verify that the machine does in fact perform as it was designed to a series of investigations were performed, Section 3.10. The results of these investigations are presented in Section 4.1 and discussed in Section 5.1.
3.4. Crack accommodation testing procedure

In order to carry out an evaluation in the fatigue machine the following steps have to be followed.

- The air pressure to the fatigue machine is set to 0.138MPa (20 psi) and the grips are moved to their closest position.

- Collets and barrels are placed on each end of the reinforcing bar so that it just fits into the grips. The air pressure is reduced to zero and the fatigue machine set to move the grips apart. The specimen is put into the grips and the air pressure is increased slowly until the grips begin to move apart. The grips are now stopped in this position while the LVDT's are set up.

- The LVDT's are clamped into their mounting blocks so that the armatures are approximately in the centre of their stroke. The LVDT's are zeroed by rotating the adjusting the screws in the LVDT mounts until the data logger display reads zero displacement.

- The fatigue machine controller is now set so that it will only move the grips apart when air pressure is applied to the actuator (i.e. the grips will only be pulled together by the elasticity of the reinforcing bar).

- With the controller switched on the air pressure is slowly increased on subsequent cycles until a crack has grown through the thickness of the specimen. This happens because on every cycle the strain in the mortar is increased until fracture occurs. This can be seen as a sudden increase in the LVDT readings, observing the crack underneath the coating, by hearing a cracking sound or by some combination of all three of these factors.

- The air pressure is increased again, while the machine is cycling, in steps of approximately 0.034MPa (5 psi) until the maximum required crack opening is reached by plastically deforming the reinforcing bar. Now the machine is
stopped with the crack in its closed position so that the desired temperature can be set in the temperature cabinet. When the temperature is reached the test can proceed as required.

Observations of the coating are made every 500 cycles with an optical microscope to look for damage. The microscope used was a low power stereo type which could be swung away from the temperature cabinet so that the door could be closed for non-ambient temperature testing.

3.4.1. Crack accommodation test end point

As soon as a coating becomes discontinuous it will fail to do its job, i.e. it will let deleterious agents pass through into the concrete below. Failure to do its job seems to be the obvious definition of the test end point. However, finding a reliable method of detecting this point without affecting the result of the test (for example water penetration would cause disturbance to both the test itself and the coating) proved to be difficult. For the purposes of this work, failure was said to occur when a hole through the coating could be seen using a microscope with a magnification of times two.

3.5. Crack bridging tests using the fatigue machine

The fatigue machine can be used to carry out crack bridging tests. When an absolute value of crack bridging ability is required, i.e. the crack width that will cause the coating material to break, a slightly different operating procedure to that used for the crack accommodation tests is required. The crack was initiated in the same way as for the crack accommodation tests, Section 3.4. At this point the cylinder pressure was exhausted to atmosphere so that the crack would close. The specimen was allowed to reach the required temperature for the test. The air pressure was then increased slowly in steps of approximately 0.034MPa (5psi) such that the crack width was slowly increased. During this procedure the coating was examined by microscope for failure. The failure criterion used was the same as that used in the crack accommodation tests, Section 3.4.1.
3.6. Free film preparation

In order to carry out free film tests a procedure for casting the films repeatably was required. The apparatus for doing this is shown in Figure 3.7. It uses a piece of float glass 6mm thick to give a flat base. A small amount of white spirit is applied to the glass and a piece of melinex coated with a release agent is squeegeed onto this. The white spirit acts to hold the melinex in close contact with the glass. A guide wire is placed down opposite sides of the glass to give a uniform film thickness. The actual wire diameter is not critical as the paint film thickness can be measured once it has cured. As the materials used contained approximately 50% solids by volume a wire diameter close to twice the required coating thickness was used.

![Figure 3.7. Apparatus for casting free films](image)

Casting was carried out by pouring an excess amount of the coating material across the width of the glass plate so that it touched the guide wires. A steel rule was used to squeegee the liquid down the glass plate to the other end. Only one pass was made or the surface of the film became unacceptable. A dust cover was placed over the apparatus which was left for 2 days in laboratory air to cure. A scalpel was then used to cut the film away.
from the guide wires and to remove the un-even regions at each end. The film was left for a further 12 days to cure before it was used.

Coupons were cut from the sheet by using steel bar of the required width for a template and cutting around this with a scalpel. It was thought that this was a more reproducible method than drawing the outline of the coupon and cutting around this.

The thickness of the coupons was measured using a digital height gauge with 12mm diameter anvils. The height gauge had a resolution of 0.02mm. This device did not visibly deform the surface of the coupon as did a micrometer with smaller anvils. If the anvils were left in contact with the film the reading was seen not to change. This showed that excess pressure was not being applied and that an accurate reading of coating thickness was obtained.

3.7. Free film tensile testing procedure

Free film tests were carried out in an Instron tensile testing machine. Testing was carried out in accordance with BS 2782 part 3 using straight sided coupons. The crosshead speed was varied according to the length of the coupon in order to keep the strain rate the same in all of the tests. The extension of the film was obtained from the crosshead movement during the test.

3.8. Dynamic Mechanical Thermal Analysis

Dynamic Mechanical Analysis is described by Wendlandt and Gallagher as 'a technique in which the dynamic modulus and/or damping of a substance is measured under oscillatory load as a function of temperature as the substance is subjected to a controlled temperature program'. The apparatus used for the glass transition assessment was a Polymer Laboratories Dynamic Mechanical Thermal Analyser (DMTA), Figure 3.8. The functions of this apparatus are summarised by Wendlandt and Gallagher. This is a fixed frequency, variable amplitude analyser consisting of a dynamic measuring head, a microprocessor controlled analyser and a temperature programmer. The frequency is selectable from 0.033
to 90 Hz and the displacement can be set to one of four discrete steps up to and including 0.25mm. The apparatus applies a sinusoidal varying displacement via a driven-arm clamped centrally to a thin rectangular specimen fixed at both ends to a passive frame, Figure 3.8. The analyser is programmed to apply a fixed frequency of specimen flexure. This is done by varying the current supplied to an electro-magnet which moves the driven-arm. The resulting displacement of the driven arm, which is controlled by the viscoelastic response of the specimen, is monitored using an opto-electronic device operating from a reference attached to the arm.

For a linear viscoelastic specimen the strain will alternate sinusoidally but will be out of phase with the stress, Mulheron. This phase lag results from the time necessary for molecular rearrangements and is associated with relaxation phenomena. By comparing the phase angle between the drive signal and the actual response of the driven-arm the analyser is able to determine the loss tangent \( \tan \delta \), which is the ratio of the energy dissipated to the maximum potential energy stored per cycle. The stress in the specimen can be considered to consist of two components, one in-phase and the other 90° out of phase with the strain.
By dividing these stresses by the strain, real (in-phase) and imaginary (out-of-phase) moduli are obtained, $E'$ and $E''$ respectively. $E'$ is the storage modulus and characterises the ability of the polymer to store energy (elastic behaviour) while $E''$ is the loss modulus and characterises the ability of the material to dissipate energy (viscous behaviour), Hatakeyama and Quinn. When the apparatus has been calibrated for the specimen dimensions the analyser can determine the real component $E'$. Since both $\tan \delta$ and $E'$ are dependent on the structure of the polymer, structural changes such as those that occur at glass transition can be readily detected with this technique. The data from the DMTA (temperature, $\tan \delta$ and modulus) are recorded by a data logging system similar to that used to log the data from the fatigue tests.

3.8.1. DMTA test procedure

A coupon of the coating under investigation is cut from a free film sheet as detailed in Section 3.6 and this is glued to the two fixed clamping bars of the specimen clamp using a cyanoacrylate adhesive. This was done to overcome the slippage that occurred during initial tests as the coupon deformed under the pressure of the clamps with increasing...
temperature. The DMTA clamping arrangement is shown in figure 3.9. The clamp was then attached to the dynamic measuring head and the driven arm clamped to the specimen. The tests were carried out with the programmer set to auto displacement and a frequency of 0.3hz and with the temperature controller set to a heating rate of 2°C per minute. The furnace was clamped onto the dynamic measuring head and the specimen cooled by pouring liquid nitrogen into the cooling chamber of the furnace. When the temperature had fallen to below -60°C the data logger was started, then the analyser and then the temperature programmer. When the test was finished the data was downloaded into the spreadsheet package for analysis.

3.9. Artificial weathering

It was necessary to evaluate the effect of weathering on the performance of the coating materials tested, both as free films and bonded onto a mortar substrate. It was impractical to use natural weathering as the time taken would be too great and the exposure would be un-repeatable. Artificial weathering was used and the particular form chosen was a QUV Weatherometer. The weatherometer and the testing procedure used both conformed to ASTM G 53 - 84. The standard defines the dimensions of the weatherometer and the fluorescent tube type and positioning. The specimens weathered for this work were subjected to equal periods of ultra-violet exposure at 60°C and condensation exposure at 50°C for a specified time. Times are specified as the number of hours exposure to ultra-violet light so the actual time in the weatherometer will be twice this value.

3.10. Test programme undertaken

As the testing machine was built from scratch there was no written specification or documentation to confirm its performance. It was therefore necessary to carry out tests to prove that it was fit for its intended propose and that it could perform reliably and consistently. The procedures for this evaluation are outlined in Section 3.10.1.
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The crack bridging tests carried out during this program were of two types, those that show the width of crack that causes failure of the material and those that show that the material can bridge a crack of a certain width without failure.

The tests carried out using the fatigue machine were of both types, various combinations of temperature, material type and thickness and level of artificial weathering being used. The tests carried out using the BRE apparatus were of the former type where the results are given as the crack width that causes failure in one material for three temperatures and two coating thicknesses.

A series of large crack opening tests were carried out on modified fatigue test specimens to allow the comparison of the extensibility of coatings bonded to a substrate with the extensibility of free films. These tests were carried out in an Instron tensile testing machine.

It was also necessary to carry out some tests on free film materials to assess extensibility and glass transition. The extensibility tests were carried out in an Instron tensile testing machine and the glass transition temperature assessments were carried out in a Dynamic Mechanical Thermal Analyser.

3.10.1. Waveform of crack opening

With this fatigue machine it was impossible to get a symmetrical waveform due to the fact that the actuator is powered by a compressible medium and is only powered in one direction. This does not cause a problem as the test results are treated comparatively. An experiment was devised in order to evaluate the shape of the waveform. This involved setting up a test using the same conditions of crack opening and timer settings as a normal crack accommodating test but logging the crack opening data from the LVDT's at 20 Hz. This will give 66 data points every cycle and so will allow the shape of the waveform to be seen. The results for this test are presented in Section 4.1.1.
3.10.2. Crack opening repeatability within a single test

In order to evaluate this a coated sample was cracked and a test set up such that the crack opening cycled between 0.4mm and 0.7mm. The signals from both LVDT's were logged at a frequency of 1 Hz. Graphs of the maximum and minimum crack openings against number of cycles were plotted from the results. These results are presented in Section 4.1.2.

3.10.3. Crack opening repeatability across several tests

To show that the crack opening was able to be produced across several tests the data from a series of crack tests was required. This aspect of the characterisation of the testing machine will be discussed in Section 5.1.2.

The following section details the tests carried out to assess the crack bridging ability of several coating materials using three different pieces of apparatus.

3.10.4. Crack bridging tests using the fatigue machine

The crack bridging tests carried out in the fatigue machine are listed in Table 3.1. Two types of result can be obtained from this type of test, the crack width that causes the coating to fail and a crack width at which the coating is able to survive. The former result gives an absolute limit to crack bridging ability whilst the latter result gives a crack width at which the coating is able to crack bridge without defining an upper limit.
<table>
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<th>Temperature °C</th>
<th>Thickness (mm)</th>
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</thead>
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<tr>
<td>A</td>
<td>15</td>
<td>0.04</td>
</tr>
<tr>
<td>A</td>
<td>15</td>
<td>0.175</td>
</tr>
<tr>
<td>A</td>
<td>15</td>
<td>0.4</td>
</tr>
<tr>
<td>A</td>
<td>30</td>
<td>0.04</td>
</tr>
<tr>
<td>A</td>
<td>30</td>
<td>0.175</td>
</tr>
<tr>
<td>A</td>
<td>30</td>
<td>0.4</td>
</tr>
<tr>
<td>C1</td>
<td>20</td>
<td>0.4</td>
</tr>
<tr>
<td>D1</td>
<td>20</td>
<td>0.4</td>
</tr>
<tr>
<td>D2</td>
<td>20</td>
<td>0.4</td>
</tr>
<tr>
<td>C1QUV</td>
<td>20</td>
<td>0.4</td>
</tr>
<tr>
<td>D2QUV</td>
<td>20</td>
<td>0.4</td>
</tr>
<tr>
<td>C2</td>
<td>-15</td>
<td>0.3</td>
</tr>
<tr>
<td>C2QUV500</td>
<td>-15</td>
<td>0.31</td>
</tr>
<tr>
<td>C2QUV3000</td>
<td>-15</td>
<td>0.31</td>
</tr>
<tr>
<td>B</td>
<td>10</td>
<td>single coat</td>
</tr>
<tr>
<td>B</td>
<td>10</td>
<td>single coat</td>
</tr>
<tr>
<td>B</td>
<td>10</td>
<td>single coat</td>
</tr>
<tr>
<td>B</td>
<td>25</td>
<td>single coat</td>
</tr>
<tr>
<td>B</td>
<td>25</td>
<td>single coat</td>
</tr>
<tr>
<td>B</td>
<td>25</td>
<td>single coat</td>
</tr>
<tr>
<td>B</td>
<td>25</td>
<td>single coat</td>
</tr>
<tr>
<td>B</td>
<td>25</td>
<td>single coat</td>
</tr>
<tr>
<td>BQUV500</td>
<td>25</td>
<td>single coat</td>
</tr>
<tr>
<td>BQUV500</td>
<td>25</td>
<td>single coat</td>
</tr>
<tr>
<td>BQUV500</td>
<td>25</td>
<td>single coat</td>
</tr>
<tr>
<td>BQUV2000</td>
<td>25</td>
<td>single coat</td>
</tr>
<tr>
<td>BQUV2000</td>
<td>25</td>
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</tr>
<tr>
<td>BQUV2000</td>
<td>25</td>
<td>single coat</td>
</tr>
</tbody>
</table>

Table 3.1. Crack bridging tests carried out using the fatigue machine
3.10.5. Crack bridging tests using the Building Research Establishment apparatus

<table>
<thead>
<tr>
<th>Thickness (mm)</th>
<th>Temperature (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.2</td>
<td>-20</td>
</tr>
<tr>
<td>0.4</td>
<td>-20</td>
</tr>
<tr>
<td>0.2</td>
<td>0</td>
</tr>
<tr>
<td>0.4</td>
<td>0</td>
</tr>
<tr>
<td>0.2</td>
<td>18</td>
</tr>
<tr>
<td>0.4</td>
<td>18</td>
</tr>
</tbody>
</table>

Table 3.2. Crack bridging tests carried out using the Building Research Establishment apparatus

Table 3.2 shows the tests carried out using the Building Research Establishment apparatus. These tests were carried out on two coating thicknesses and at three temperatures.

3.10.6. Large crack opening tests

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Thickness (mm)</th>
<th>Crosshead Speed (mm/min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.375</td>
<td>2</td>
</tr>
<tr>
<td>2</td>
<td>0.375</td>
<td>2</td>
</tr>
<tr>
<td>3</td>
<td>0.375</td>
<td>2</td>
</tr>
</tbody>
</table>

Table 3.3 Large crack opening tests

A series of large crack opening tests were performed on the material C1. These were carried out at 20°C in an Instron tensile testing machine. The initial crack was initiated and propagated through the thickness of the fatigue specimen in the fatigue machine as normal. The two parts of the mortar prism either side of the crack were then rigidly clamped together so that when the reinforcing bar was cut with a diamond saw there was no relative movement of the two parts of the prism. The cut and clamped specimen was the loaded into the tensile testing machine. The clamps could now be removed and testing commenced. The tests are detailed in Table 3.3.
3.10.7. Crack accommodation

Details of the crack accommodating tests are given in this section. Crack accommodating tests were carried out on several materials, some of which were artificially weathered in a QUV Weatherometer, Section 3.9. Specimens were artificially weathered for 500 light hours unless stated otherwise. All crack openings were a nominal 0.4 - 0.7mm unless stated otherwise.

<table>
<thead>
<tr>
<th>Material</th>
<th>Temperature (°C)</th>
<th>Number of tests</th>
</tr>
</thead>
<tbody>
<tr>
<td>C1</td>
<td>-20</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>-10</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>-3</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>4</td>
</tr>
<tr>
<td>C2</td>
<td>-15</td>
<td>2^a</td>
</tr>
<tr>
<td></td>
<td>-15</td>
<td>1^b</td>
</tr>
<tr>
<td>D1</td>
<td>-30</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>-20</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>-10</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>4</td>
</tr>
<tr>
<td>D2</td>
<td>-30</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>-20</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>-10</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>0</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>6</td>
</tr>
</tbody>
</table>

Table 3.4. Fatigue tests carried out on un-weathered specimens

Where ^a indicates a crack opening of 0.07 - 0.29mm and ^b indicates a crack opening of 0.2 - 0.4mm.
Table 3.5. Fatigue tests carried out on weathered specimens

<table>
<thead>
<tr>
<th>Material</th>
<th>Temperature (°C)</th>
<th>Number of Tests</th>
</tr>
</thead>
<tbody>
<tr>
<td>C1</td>
<td>-20</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>-3</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>0</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>4</td>
</tr>
<tr>
<td>C2</td>
<td>-15</td>
<td>2&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td></td>
<td>-15</td>
<td>2&lt;sup&gt;bc&lt;/sup&gt;</td>
</tr>
<tr>
<td>D2</td>
<td>-30</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>-20</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>-10</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>25</td>
<td>3</td>
</tr>
</tbody>
</table>

Where <sup>c</sup> indicates 3000 light hours artificial weathering.

Table 3.4 shows tests that were carried out on un-weathered specimens and Table 3.5 shows those tests that were carried out on specimens that had been weathered artificially.

3.10.8. Mechanical Properties

Free films cast as described in Section 3.6 were tested in an Instron tensile testing machine to show to what extent it was possible to strain the material in its un-constrained state. This complements the tests carried out on the bonded films described in Section 3.10.6 on fatigue specimens where the reinforcing bar had been cut to allow large crack openings to be achieved. A summary of the tests carried out are shown in the Table 3.6. The tests were carried out at 20°C using platen type grips. The loading was carried out in accordance with BS 2782, Determination of tensile strength and elongation of plastics films.
### 3.10.9. Glass transition assessment

Several of the coating materials were assessed to find their glass transition temperatures. This information is important as these materials are used over a range of temperatures. Some of these materials were assessed both before and after artificial weathering. The tests are summarised in Table 3.7.

<table>
<thead>
<tr>
<th>Material</th>
<th>Heating Rate ( \degree \text{C/min} )</th>
<th>Weathering (hours QUV)</th>
<th>Number of tests</th>
</tr>
</thead>
<tbody>
<tr>
<td>C1</td>
<td>2</td>
<td>0</td>
<td>3</td>
</tr>
<tr>
<td>C1QUV</td>
<td>2</td>
<td>500</td>
<td>3</td>
</tr>
<tr>
<td>D1</td>
<td>2</td>
<td>0</td>
<td>3</td>
</tr>
<tr>
<td>D2</td>
<td>2</td>
<td>0</td>
<td>3</td>
</tr>
<tr>
<td>D2QUV</td>
<td>2</td>
<td>500</td>
<td>3</td>
</tr>
<tr>
<td>C2</td>
<td>2</td>
<td>0</td>
<td>3</td>
</tr>
<tr>
<td>C2QUV</td>
<td>2</td>
<td>500</td>
<td>3</td>
</tr>
<tr>
<td>C2QUV</td>
<td>2</td>
<td>3000</td>
<td>3</td>
</tr>
</tbody>
</table>

Table 3.7. Tests carried out to assess glass transition temperature

All of the tests were carried out at a frequency of 0.3 Hz so that the time for one cycle in the DMTA was the same as the time for one cycle in the fatigue machine during a crack accommodation test. The influence of frequency on glass transition temperature is discussed in Section 2.5.2.
4. Results

In this chapter are presented the experimental results obtained during this work. Section 4.1 details the results obtained from characterising the fatigue machine. These experiments were necessary in order to prove that the machine performed in a desirable and reliable manner. The results from the crack bridging tests can be found in Section 4.2. These tests were carried out at various temperatures, levels of artificial weathering and material thicknesses with several coating materials and pieces of apparatus. The crack accommodation tests, Section 4.3, are divided into two parts. The first part covers unweathered materials, Section 4.3.1 and the second part demonstrates the effect of artificial weathering on the crack accommodation performance of some of the coating materials.

Glass transition assessment and static response results are shown in Section 4.4. These tests were carried out on free films manufactured by casting.

4.1 Testing machine characteristics

The fatigue machine was constructed in-house and as such there was no certification available for it to guarantee its performance. In order to utilise the machine effectively and with confidence it was necessary to show that it could reproduce a crack opening throughout the duration of a test, and also across several tests. It was also necessary to know the shape of the crack opening waveform. The results of these assessments are shown in sections 4.1.1 and 4.1.2.

4.1.1. Waveform of crack opening

The result of this test is shown in Figure 4.1a. This shows that the crack opening waveform is consistent over several cycles. A more detailed view of the waveform is shown in Figure 4.1b. This shows that the crack opens quickly at first from 0.38 mm to 0.7 mm in 0.3 seconds. Over the next 0.6 seconds the crack opens only a further 0.01 mm
to its maximum value of 0.71mm. The crack now closes to its minimum value of 0.35mm in 1.5 seconds and then stays at this minimum value for a further 1 second before the next cycle begins.

4.1.2. Crack opening repeatability within a single test

The results for this test are presented as two graphs, one for each LVDT. These are shown in Figure 4.2a for the left hand LVDT and Figure 4.2b for the right hand LVDT. The steep rise in crack width from zero cycles is due to the crack being opened in fatigue until it is of the required width.
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Figure 4.1b. Detailed view of crack opening waveform

Figure 4.2a. Graph showing maximum and minimum crack opening for LVDT 1
Chapter 4: Results

Table 4.1. Results from crack bridging tests carried out on material A

<table>
<thead>
<tr>
<th>Temperature (°C)</th>
<th>Thickness (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.04</td>
</tr>
<tr>
<td></td>
<td>Crack width (mm)</td>
</tr>
<tr>
<td>0</td>
<td>0.07</td>
</tr>
<tr>
<td>0</td>
<td>0.08</td>
</tr>
<tr>
<td>0</td>
<td>0.09</td>
</tr>
<tr>
<td>15</td>
<td>0.08</td>
</tr>
<tr>
<td>15</td>
<td>0.10</td>
</tr>
<tr>
<td>15</td>
<td>0.10</td>
</tr>
<tr>
<td>30</td>
<td>0.14</td>
</tr>
<tr>
<td>30</td>
<td>0.14</td>
</tr>
<tr>
<td>30</td>
<td>0.15</td>
</tr>
</tbody>
</table>

Figure 4.2b. Graph showing maximum and minimum crack opening for LVDT 2
4.2 Crack bridging

In this section are presented the results of crack bridging tests carried out on a variety of materials using three pieces of apparatus. The materials were viscous in nature, Section 4.2.1, and visco-elastic in nature, Section 4.2.2.

4.2.1. Viscous coating

Table 4.1 shows the results obtained from crack bridging tests carried out on material A, using the fatigue testing machine. Tests were carried out at three temperatures and three coating thicknesses. It can be seen that as the test temperature was increased the crack width that the material was able to bridge also increased.

4.2.2. Viscoelastic coatings

This section presents crack bridging results obtained for the viscoelastic coatings using the dedicated testing machine in 'one shot' mode, an Instron testing machine and the Building Research Establishment apparatus. Results are presented either as crack widths that a coating is able to bridge without failure, or crack widths that cause failure of the coating.

4.2.2.1. Results obtained using the fatigue testing machine

<table>
<thead>
<tr>
<th>Material</th>
<th>Temperature °C</th>
<th>Thickness (mm)</th>
<th>Crack opening (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>C1</td>
<td>20</td>
<td>0.4</td>
<td>0.7</td>
</tr>
<tr>
<td>D1</td>
<td>20</td>
<td>0.4</td>
<td>0.7</td>
</tr>
<tr>
<td>D2</td>
<td>20</td>
<td>0.4</td>
<td>0.7</td>
</tr>
<tr>
<td>C1QUV</td>
<td>20</td>
<td>0.4</td>
<td>0.7</td>
</tr>
<tr>
<td>D2QUV</td>
<td>20</td>
<td>0.4</td>
<td>0.7</td>
</tr>
<tr>
<td>C2</td>
<td>-15</td>
<td>0.3</td>
<td>0.7</td>
</tr>
<tr>
<td>C2QUV500</td>
<td>-15</td>
<td>0.31</td>
<td>0.29</td>
</tr>
<tr>
<td>C2QUV3000</td>
<td>-15</td>
<td>0.31</td>
<td>0.29</td>
</tr>
</tbody>
</table>

Table 4.2. Results of crack bridging tests that show ability to bridge cracks of a certain width

Table 4.2 shows the results of crack bridging tests carried out on a number of materials. The data show crack widths that the materials were able to bridge without failure. This
Chapter 4: Results

means that they are not maximum values but are lower bounds. These results were obtained from the first opening cycle of the crack accommodating tests presented in Section 4.3.

<table>
<thead>
<tr>
<th>Weathering hours QUV</th>
<th>Temperature °C</th>
<th>Crack opening (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>10</td>
<td>0.1</td>
</tr>
<tr>
<td>0</td>
<td>10</td>
<td>0.03</td>
</tr>
<tr>
<td>0</td>
<td>10</td>
<td>0.06</td>
</tr>
<tr>
<td>0</td>
<td>25</td>
<td>0.19</td>
</tr>
<tr>
<td>0</td>
<td>25</td>
<td>0.18</td>
</tr>
<tr>
<td>0</td>
<td>25</td>
<td>0.22</td>
</tr>
<tr>
<td>500</td>
<td>25</td>
<td>0.1</td>
</tr>
<tr>
<td>500</td>
<td>25</td>
<td>0.16</td>
</tr>
<tr>
<td>500</td>
<td>25</td>
<td>0.07</td>
</tr>
<tr>
<td>2000</td>
<td>25</td>
<td>0.14</td>
</tr>
<tr>
<td>2000</td>
<td>25</td>
<td>0.06</td>
</tr>
<tr>
<td>2000</td>
<td>25</td>
<td>0.06</td>
</tr>
</tbody>
</table>

Table 4.3. Results of crack bridging tests on material B that show the crack width at which the coating fails

Table 4.3 shows the crack widths that cause failure in material B for two temperatures and three levels of weathering. It can be seen that the un-weathered material bridged cracks of 0.18, 0.19 and 0.22mm at 25°C. When the temperature was reduced to 10°C the material bridged crack openings of 0.1 (upper limit, the actual value was less than this but was not recorded), 0.03 and 0.06mm. For the 500 hours QUV samples tested at 25°C the maximum cracks bridged were 0.1mm, 0.07mm and 0.16mm. For the 2000 hours QUV the cracks bridged were 0.14mm, and two at 0.06mm. The maximum crack bridged at 2000 hours QUV (0.14mm) is less than the maximum crack bridged at 500 hours QUV (0.16mm).
4.2.2.2. Building Research Establishment crack bridging tests

<table>
<thead>
<tr>
<th>Thickness (μm)</th>
<th>Temperature (°C)</th>
<th>Crack width (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>200</td>
<td>-20</td>
<td>0</td>
</tr>
<tr>
<td>400</td>
<td>-20</td>
<td>0</td>
</tr>
<tr>
<td>200</td>
<td>0</td>
<td>1.52</td>
</tr>
<tr>
<td>400</td>
<td>0</td>
<td>2.54</td>
</tr>
<tr>
<td>200</td>
<td>18</td>
<td>1.52</td>
</tr>
<tr>
<td>400</td>
<td>18</td>
<td>3.56</td>
</tr>
</tbody>
</table>

Table 4.4. Results of tests carried out on material C1 using the Building Research Establishment apparatus

Table 4.4 shows the results obtained from the Building Research Establishment apparatus when testing material C1 at two thicknesses and two temperatures. The ability of the material to bridge cracks changes significantly from -20°C to 18°C. Where zero crack width is indicated, i.e. those at -20°C, it may have been that the apparatus was unable to resolve the crack width at which the coating failed. The smallest crack movement that the apparatus could resolve was 0.051mm.

4.2.2.3. Large crack opening tests

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Thickness (mm)</th>
<th>Temperature (°C)</th>
<th>Extension to failure (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.375</td>
<td>20</td>
<td>11.2</td>
</tr>
<tr>
<td>2</td>
<td>0.375</td>
<td>20</td>
<td>12.0</td>
</tr>
<tr>
<td>3</td>
<td>0.375</td>
<td>20</td>
<td>11.6</td>
</tr>
</tbody>
</table>

Table 4.5. Results of large crack opening displacement tests on material C1

Table 4.5 shows the results of crack bridging tests carried out in an Instron testing machine on material C1. The specimens were extended at 2mm/minute until the coating material failed. The extension was read from two LVDT’s as in the crack accommodation experiments. The results are fairly consistent with failures between 11 and 12mm.
4.3 Crack accommodation - Surrey method

The results from the crack accommodation tests were obtained from specimens where the original crack opening was set up at 20°C as described in section 3.4. Results are presented for both weathered and un-weathered coatings.

4.3.1. Tests carried out on un-weathered coatings

The tests in this section were carried out on coatings that were in the as applied condition and had not been subjected to any artificial weathering.

4.3.1.1. Material C1

<table>
<thead>
<tr>
<th>Temperature °C</th>
<th>Cycles to failure</th>
</tr>
</thead>
<tbody>
<tr>
<td>-20</td>
<td>0.5</td>
</tr>
<tr>
<td>-20</td>
<td>0.5</td>
</tr>
<tr>
<td>-20</td>
<td>0.5</td>
</tr>
<tr>
<td>-10</td>
<td>0.5</td>
</tr>
<tr>
<td>-10</td>
<td>0.5</td>
</tr>
<tr>
<td>-3</td>
<td>4499</td>
</tr>
<tr>
<td>-3</td>
<td>5350</td>
</tr>
<tr>
<td>20</td>
<td>4382</td>
</tr>
<tr>
<td>20</td>
<td>4626</td>
</tr>
<tr>
<td>20</td>
<td>6129</td>
</tr>
<tr>
<td>20</td>
<td>6613</td>
</tr>
</tbody>
</table>

Table 4.6. Results obtained from crack accommodating tests carried out on material C1

Table 4.6 shows two distinct levels of crack accommodating behaviour separated by several orders of magnitude. Some failures occur on the first half of the first opening cycle of the test and are referred to as half cycle failures and some fail after several thousand cycles.
4.3.1.2. Material C2

Table 4.7 shows the crack accommodating results for un-weathered material C2 at two crack openings.

<table>
<thead>
<tr>
<th>Crack opening (mm)</th>
<th>Cycles to failure</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.07 - 0.29</td>
<td>12975</td>
</tr>
<tr>
<td>0.2 - 0.4</td>
<td>1300</td>
</tr>
</tbody>
</table>

Table 4.7. Results obtained from crack accommodating tests carried out on material C2

4.3.1.3. Material D1

<table>
<thead>
<tr>
<th>Temperature °C</th>
<th>Cycles to failure</th>
</tr>
</thead>
<tbody>
<tr>
<td>-30</td>
<td>0.5</td>
</tr>
<tr>
<td>-22</td>
<td>0.5</td>
</tr>
<tr>
<td>-20</td>
<td>0.5</td>
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<tr>
<td>-20</td>
<td>0.5</td>
</tr>
<tr>
<td>-20</td>
<td>277</td>
</tr>
<tr>
<td>-10</td>
<td>13665</td>
</tr>
<tr>
<td>20</td>
<td>5419</td>
</tr>
<tr>
<td>20</td>
<td>6693</td>
</tr>
<tr>
<td>20</td>
<td>8405</td>
</tr>
<tr>
<td>20</td>
<td>24145</td>
</tr>
</tbody>
</table>

Table 4.8. Results obtained from crack accommodating tests carried out on material D1

Table 4.8 shows the results of the fatigue tests for another material. As in Table 4.6 there are two levels of crack accommodating behaviour which are separated by several orders of magnitude.
4.3.1.4. Material D2

<table>
<thead>
<tr>
<th>Temperature °C</th>
<th>Cycles to failure</th>
</tr>
</thead>
<tbody>
<tr>
<td>-30</td>
<td>0.5</td>
</tr>
<tr>
<td>-30</td>
<td>0.5</td>
</tr>
<tr>
<td>-20</td>
<td>0.5</td>
</tr>
<tr>
<td>-20</td>
<td>0.5</td>
</tr>
<tr>
<td>-10</td>
<td>4432</td>
</tr>
<tr>
<td>-10</td>
<td>5642</td>
</tr>
<tr>
<td>-10</td>
<td>6482</td>
</tr>
<tr>
<td>-10</td>
<td>8522</td>
</tr>
<tr>
<td>0</td>
<td>10802</td>
</tr>
<tr>
<td>0</td>
<td>12943</td>
</tr>
<tr>
<td>0</td>
<td>30951</td>
</tr>
<tr>
<td>20</td>
<td>2134</td>
</tr>
<tr>
<td>20</td>
<td>2199</td>
</tr>
<tr>
<td>20</td>
<td>2782</td>
</tr>
<tr>
<td>20</td>
<td>3514</td>
</tr>
<tr>
<td>20</td>
<td>9336</td>
</tr>
<tr>
<td>20</td>
<td>14589</td>
</tr>
</tbody>
</table>

Table 4.9. Results obtained from crack accommodation tests carried out on material D2

Table 4.9 shows the results of the fatigue tests for material similar to material D1 but with a modified formulation. Again we see two levels of crack accommodating behaviour although in two cases, at 0°C, the tests had to be stopped due to failures not occurring in a reasonable number of cycles.

4.3.2. Effect of artificial weathering

The data in this section was obtained from material that had been artificially weathered in a QUV weatherometer.
4.3.2.1. Material C1QUV

<table>
<thead>
<tr>
<th>Temperature °C</th>
<th>Cycles to failure</th>
</tr>
</thead>
<tbody>
<tr>
<td>-20</td>
<td>0.5</td>
</tr>
<tr>
<td>-3</td>
<td>6</td>
</tr>
<tr>
<td>-3</td>
<td>8</td>
</tr>
<tr>
<td>-3</td>
<td>12</td>
</tr>
<tr>
<td>0</td>
<td>0.5</td>
</tr>
<tr>
<td>0</td>
<td>200</td>
</tr>
<tr>
<td>0</td>
<td>842</td>
</tr>
<tr>
<td>0</td>
<td>1493</td>
</tr>
<tr>
<td>0</td>
<td>5652</td>
</tr>
<tr>
<td>20</td>
<td>3410</td>
</tr>
<tr>
<td>20</td>
<td>3603</td>
</tr>
<tr>
<td>20</td>
<td>6481</td>
</tr>
<tr>
<td>20</td>
<td>9142</td>
</tr>
</tbody>
</table>

Table 4.10. Results obtained from crack accommodating tests carried out on material C1QUV

Table 4.10 shows the results for material C1 after it had been exposed to 500 light hours in a QUV Weatherometer. As with un-weathered material C1 there are two levels of crack accommodating ability. However, in this case there is not a clear distinction between the two levels.

4.3.2.2. Material C2QUV

<table>
<thead>
<tr>
<th>Hours (QUV)</th>
<th>Cycles to failure</th>
</tr>
</thead>
<tbody>
<tr>
<td>500</td>
<td>12975</td>
</tr>
<tr>
<td>500</td>
<td>12300</td>
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<tr>
<td>3000</td>
<td>9113</td>
</tr>
<tr>
<td>3000</td>
<td>10759</td>
</tr>
</tbody>
</table>

Table 4.11. Results of crack accommodation tests carried out on weathered material C2

Table 4.11 shows the results obtained for material C2 at -15°C. The material was exposed to 500 and 3000 hours of artificial weathering in a QUV weatherometer.
4.3.2.3. Material D2QUV

<table>
<thead>
<tr>
<th>Temperature °C</th>
<th>Cycles to failure</th>
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</thead>
<tbody>
<tr>
<td>-30</td>
<td>0.5</td>
</tr>
<tr>
<td>-30</td>
<td>0.5</td>
</tr>
<tr>
<td>-30</td>
<td>0.5</td>
</tr>
<tr>
<td>-20</td>
<td>0.5</td>
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<tr>
<td>-20</td>
<td>0.5</td>
</tr>
<tr>
<td>-18</td>
<td>0.5</td>
</tr>
<tr>
<td>-10</td>
<td>151</td>
</tr>
<tr>
<td>-10</td>
<td>463</td>
</tr>
<tr>
<td>-10</td>
<td>717</td>
</tr>
<tr>
<td>-10</td>
<td>1314</td>
</tr>
<tr>
<td>0</td>
<td>20172</td>
</tr>
<tr>
<td>24</td>
<td>43360</td>
</tr>
<tr>
<td>24</td>
<td>50773</td>
</tr>
<tr>
<td>25</td>
<td>50481</td>
</tr>
</tbody>
</table>

Table 4.12. Results obtained from crack accommodating tests carried out on weathered material D2

Table 4.12 shows the results of fatigue tests carried out on material D2 that has been exposed to 500 light hours in a QUV Weatherometer. This material also shows two levels of crack accommodating. It should be noted that the 24°C and 25°C results do not show failures but the number of cycles at which the test was halted. These are lower limit results. The tests were stopped as they were taking an excessive time to fail.

4.4 Free film tests

4.4.1. Dynamic mechanical thermal analysis

The data from the glass transition assessments was obtained following the procedure in section 3.10.9. This allowed graphs of tanδ against temperature to be constructed. A typical graph is shown in Figure 4.3. The glass transition temperature was taken as the temperature at which tanδ reaches a maximum value, i.e. when the material exhibits maximum mechanical damping. The tests were run on several samples of each material and an average value taken. These averages are presented in Table 4.13.
Chapter 4: Results

Figure 4.3. A typical \( \tan \delta \) against temperature graph

<table>
<thead>
<tr>
<th>Material</th>
<th>Hours QUV</th>
<th>Glass Transition Temperature (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>C1</td>
<td>0</td>
<td>4.2</td>
</tr>
<tr>
<td>C1QUV</td>
<td>500</td>
<td>5.7</td>
</tr>
<tr>
<td>D1</td>
<td>0</td>
<td>-7.0</td>
</tr>
<tr>
<td>D2</td>
<td>0</td>
<td>-7.0</td>
</tr>
<tr>
<td>D2QUV</td>
<td>500</td>
<td>-3.6</td>
</tr>
<tr>
<td>C2</td>
<td>0</td>
<td>-25</td>
</tr>
<tr>
<td>C2QUV</td>
<td>500</td>
<td>-23.5</td>
</tr>
<tr>
<td>C2QUV</td>
<td>3000</td>
<td>-23.5</td>
</tr>
</tbody>
</table>

Table 4.13. Results from DMTA assessments

(Typical variation in measured value of Glass Transition Temperature = ±1°C)
4.4.2. Static tensile response

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Original Length (mm)</th>
<th>Original Thickness (mm)</th>
<th>Final Length (mm)</th>
<th>Strain /V</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>55</td>
<td>0.74</td>
<td>499</td>
<td>8.1</td>
<td>max. capacity</td>
</tr>
<tr>
<td>2</td>
<td>54</td>
<td>0.69</td>
<td>607.1</td>
<td>10.2</td>
<td>max. capacity</td>
</tr>
<tr>
<td>3</td>
<td>27.3</td>
<td>0.7</td>
<td>583.3</td>
<td>20.4</td>
<td>failed</td>
</tr>
<tr>
<td>4</td>
<td>52.3</td>
<td>0.68</td>
<td>555.3</td>
<td>9.6</td>
<td>failed</td>
</tr>
<tr>
<td>5</td>
<td>52.7</td>
<td>0.71</td>
<td>605.7</td>
<td>10.5</td>
<td>max. capacity</td>
</tr>
<tr>
<td>6</td>
<td>28.8</td>
<td>0.71</td>
<td>401.8</td>
<td>13.0</td>
<td>failed</td>
</tr>
</tbody>
</table>

Table 4.14. Static tensile data obtained from free films of material C1

Table 4.14 shows the results of tests made on material C1 free films in an Instron testing machine. Several of the films could not be extended to failure as the crosshead did not have a sufficient range of movement. The results do however demonstrate the very large extensions that are possible with these types of materials.
5. Discussion

The aim of this work was to develop a reliable method for assessing the crack bridging and crack accommodating behaviour of viscoelastic coatings for reinforced concrete. The initial work concentrated on the design, construction and characterisation of a suitable test machine and associated test specimen arrangement.

Once the testing machine had been constructed and before a testing program could be undertaken, the combination of the machine, test specimen and methodology had to be shown to work in a reliable and reproducible manner. The procedures for assessing this and the subsequent results are presented in Sections 3.10 and 4.1 respectively and are discussed in Section 5.1.

Having proven the reliability and reproducibility of the test methodology a testing program could be undertaken to assess the behaviour of typical commercial coatings. Two discrete types of investigation were carried out. The first set of tests investigated the ability of coating materials to bridge cracks. The results of these tests are shown in Section 4.2 and are discussed in Section 5.2.1 and 5.2.2 against the associated background theory of crack bridging. The second set of tests assessed the crack accommodating performance of coating materials. The results of these tests are presented in Section 4.3 and are discussed in Section 5.3.

5.1. Characterisation of the testing machine

In order to demonstrate that the fatigue testing machine could operate in a satisfactory manner and provide reliable results, several experiments were carried out. The experiments are described in Section 3.10 and the results are presented in Section 4.1.
5.1.1. Crack opening repeatability within a single test

Figures 4.2a and 4.2b show how the set crack opening varies over 8000 cycles of a test. It can be seen that the crack openings vary very little over the 8000 cycles. LVDT 1 (left hand LVDT), Figure 4.2a, gave a crack opening of 0.41 to 0.72 mm ± 0.005" and LVDT 2 (right hand LVDT), Figure 4.2b, gave a crack opening of 0.36 to 0.7 ± 0.01. A variation in maximum/minimum crack opening was observed with a period of approximately 92 minutes. The source of this variation is not known, however, it seems unlikely to be caused by the testing machine itself as nothing within the hardware is thought to operate with this period. A possibility is that the dead band on the compressor pressure switch is too great and the air pressure in the main is allowed to drop by too large a value. The regulator on the testing machine requires a certain excess pressure in order to operate correctly. If this pressure is not maintained then the force exerted by the cylinder would be reduced and as a consequence the crack opening would also be reduced. However, the maximum variation is only 2.9% and as results obtained under similar conditions of temperature and crack opening give similar fatigue lives, Section 5.1.2, this variation does not appear to effect experimental results.

5.1.2. Crack opening repeatability over several tests

It was necessary to examine the possibility of differing crack widths on different test pieces having an effect on the results of the fatigue tests as this would make comparison of the results complicated. Figure 5.1a shows a graph of the variation in mean crack width as a function of increasing number of cycles to failure for several test pieces coated with the same material. This Figure reveals no apparent trend in the crack openings with increasing cycles to failure. Figure 5.1b shows the variation in the mean of each crack opening presented in Figure 5.1a. Again, there is no apparent change in the mean value with increasing cycles to failure.
Chapter 5: Discussion

Figure 5.1a. Variations in mean crack width shown against number of cycles to failure

Formula:

\[ y = mx + c \]

Where:
- \( m = -0.9 \times 10^{-6} \)
- \( c = 0.536 \)

Figure 5.1b. Variation of the means of the tests shown in Figure 5.1a
5.1.3. Validity of crack accommodating lifetime data

In order to prove that the testing machine generates reliable data it is necessary to show that the results of tests carried out under the same conditions are similar. Taking as an example the crack accommodating lifetime data for the series of tests carried out on material C1, Figure 5.16, we see that the data fall into discrete groups. This demonstrates that the data produced by the machine is reliable and repeatable.

5.1.4. Conclusions from fatigue testing machine characterisation

From the characterisation of the test procedure it can be seen that the specimen and testing machine fulfil the requirements set out in Sections 3.1 and 3.2 respectively. It was shown, in Section 5.1.1, to be able to repeatedly open a crack in a controlled manner with a precision of ±2.9%. The machine was able to reproduce a crack width and opening across several tests and additionally there was no correlation between variations in crack width and number of cycles to failure as shown by Figures 5.1a and 5.1b. If data from a series of crack accommodation tests is examined, Figure 5.16, it can be seen that duplicated tests on one material gives results that fall into discrete groups. The testing machine was shown to be able to run for a complete test without adjustment and so could be left un-attended.

These findings show that the testing machine is fit for its intended purpose and allows a test program to be undertaken.

5.2. Crack bridging performance

In discussing the observed crack bridging behaviour of viscoelastic coatings it is necessary to review the theory of crack bridging. Without an understanding of the mechanisms involved little use can be made of the experimental results.
5.2.1. Theory of crack bridging

Considering the case of a coating perfectly bonded to a substrate the problem exists that theoretically an infinite strain occurs in the coating when the substrate crack first forms as there is no coating gauge length that can be deformed. This infinite strain arises because when the crack has opened there is a crack of width \( w \) being spanned by a length of coating also of length \( w \) but with an original length of zero. In practice many coatings are known to survive a crack opening in the substrate beneath them without failure. This implies that the strain in the coating is finite and logically the crack must be spanned by a finite length of coating. The problem however is, where does this original length come from that is to act as the gauge length? Some possibilities are:

a) The lower surface of the coating tears,

b) Material breaks away from the edges of the substrate crack,

c) The coating debonds along its interface with the substrate (or primer)

These ideas are discussed in sections 5.2.1.1, 5.2.1.2 and 5.2.1.3.

5.2.1.1. Tearing of the coating

If the lower surface of the coating were to tear through part of its thickness the edges of the tear may contribute to a gauge length, Figure 5.2. The crack may be expected not to propagate through the complete thickness of the coating if the stress intensity at the crack tip were to fall below its critical value. This could lead to a substrate crack opening of up to twice the length of the coating crack, that is,

\[ w \leq 2a \]

5.2.1.2. Material breaking away from the crack/coating interface

The second option is that material becomes detached from the edges of the substrate crack when it forms. This may be possible due to fragmentation of the substrate occurring when the substrate crack forms, Figure 5.3. The substrate is no longer a continuous layer bonded to the coating and so the coating is no longer fully constrained. The un-bonded coating can deform and so act as the gauge length for coating deformation.
Chapter 5: Discussion

Figure 5.2. Coating with tear over a substrate crack

Figure 5.3. Fragmented substrate beneath the coating
5.2.1.3. Debonding of the coating from the substrate

The third option is that of a crack propagating along the coating/substrate interface so forming the gauge length required. Figure 5.4 shows the substrate crack closed beneath the debonded region of the coating. When the crack is open the debonded length allows the coating to deform.

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So, if these two criteria are met a crack will propagate along the interface between the coating system and the concrete substrate. In a commercial coating system the crack may actually be propagating along the interface between the top coat and primer of the coating system, but the result will be debonded coating.

When either the energy release rate or the stress intensity factor falls below the critical value the crack will cease to propagate and this will be the initial value of the debond length for the specimen geometry in question. The debond length may stay at this value for the remainder of the test or it may grow during fatigue.

It seems then, that a length of coating not bonded to the substrate is required so that an infinite strain in the coating is avoided when the substrate crack first forms. This suggests that the bond between the coating and the substrate should not be too strong as a certain amount of adhesion loss is required. Indeed the manufacturer of one of the viscoelastic coatings tested in this program made it clear that the primer was an adhesion modifier, in the sense that it reduced the interfacial strength to a level that would allow debonding to take place.

If a crack opening and debond length is assumed the required strain to failure of the coating can be predicted. Figure 5.5 shows this information in graphical form. The debond length, \( l \), refers to the total length of coating debonded from the substrate (at both edges of the crack). For example, a 1.0mm debond would be made up of two individual 0.5mm debonds. To bridge a crack 0.7mm wide with a debond length of 0.1mm the coating would require a failure strain in excess of 700%. For the same crack width and a debond length of 1mm the failure strain of the coating would have to be greater than 70%. This shows that even for small crack openings a significant coating strain to failure is required. For example, a crack opening of 0.1mm with a debond length 1mm requires a strain to failure of the coating greater than 20% in order not to fail.

An attempt was made to observe debonded areas of coating at the edges of the cracks in some of the material C1 samples used in the crack accommodating tests, Section 4.3.1.1.
The fatigue specimen was fixed with its crack in the open position and the section containing the crack was cut out. This section was mounted in a cold cure resin and the polished using silicon carbide paper and water. The minimum amount of grinding necessary to get a flat surface was used. The mounted sections were sputter coated and placed in the chamber of a scanning electron microscope. No evidence of debonding was seen in any of the sections. This could be because no debonding is present or that it could not be seen as the maximum size of aggregate used in the fatigue specimens was 5mm and it is unlikely that any debonding that was shorter than this would be discernible. This is because it is possible for pieces of the aggregate to become detached when the crack forms and when it is fatigued. This could disguise any debonding. The only way to avoid this is by using a homogeneous substrate, for example a steel plate, but then the substrate would not be representative of substrates found in the real world.

The stress in the coating will vary depending on what type of material the coating is formulated from. The response of an elastic coating is shown in Figure 5.6. When the crack is in the closed position the stress in the coating is zero. The crack is opened at time $t_0$ and the stress rises to its maximum value and remains there. The stress is proportional to the strain and coating stiffness and is independent of time. If the coating were viscous the stress would rise when the crack was opened and then fall with time. In this case the stress is time dependent. The change in length of the coating is permanent. In the case of the material being viscoelastic in nature the response would be a combination of the elastic and viscous cases. The stress would rise at $t_0$ when the crack is opened and then fall with time until an equilibrium value is reached. If the crack were subsequently closed the elastic part of the deformation would be recovered leaving the deformation that occurred due to the viscous component as a permanent set. This can be seen in Figure 2.13, region c'.
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Figure 5.5. Predicted coating failure strain for a given crack opening and debond length

Figure 5.6. The stress response of an elastic, a viscous and a viscoelastic material to the opening of a crack
5.2.2. Discussion of results of tests carried out on viscous and viscoelastic coatings

This section discusses the results obtained from the crack bridging tests described in Section 3.10, the results for which are presented in Section 4.2.

5.2.2.1. Material A

The results obtained from material A are presented in Figure 5.7. It can be seen that for any one of the three temperatures at which testing was carried out, an increase in coating thickness allows an increase in the size of crack that can be bridged. This suggests a thicker coating subjected to a lower stress. We can also see that for any one of the three thicknesses tested, an increase in temperature allows an increase in the crack width that can be bridged. This is because an increase in temperature will lead to a reduction in modulus which will reduce the stress carried by the coating for a given crack width. An increase in temperature may also allow the coating to flow more easily. If the temperature were reduced sufficiently so that the material becomes brittle it would be un-able to crack bridge.
5.2.2.2. Material B

Figure 5.8 shows the results from crack bridging tests on material B.

![Graph](image)

Figure 5.8. Results from tests carried out on material B

It can be seen that an increase in temperature allows an increase in the crack width that can be bridged. As the temperature of the coating material is increased it can survive larger crack openings than it could at lower temperatures. This was also true of material A. If the temperature is reduced there will be a point at which the coating materials become unable to bridge cracks due to them becoming brittle. As the temperature is reduced the modulus increases leading to a higher stress in the coating for the same crack opening and causing failure of the coating due to it reaching the limit of its tensile strength. The influence of artificial weathering on crack bridging behaviour can also be seen clearly in this Figure. Specimens that had not been weathered could bridge larger cracks than those exposed to 2000 hours of QUV weathering. This is due to degradation of the coating by the artificial weathering process as described in Section 2.5.4. As already discussed in Section 3.9, the artificial weathering process involves exposure to moisture, heat and ultra violet radiation. These cause degradation of the coating and consequently its ductility is reduced. Artificial
weathering can be seen to have a detrimental effect on the crack bridging ability of this material.

5.2.2.3. Building Research Establishment tests with Material C1

Figure 5.9. Results from tests carried out on coatings of material C1 of 0.2mm and 0.4mm thickness

Figure 5.9 shows the behaviour of material C1 when tested using the Building Research Establishment apparatus. It can be seen that at -20°C the coating is not able to crack bridge. The transition to crack bridging behaviour occurs between -20°C and 0°C, where crack bridging is first observed. When the temperature is increased sufficiently the coating begins to show crack bridging behaviour. It can be seen from Figure 5.9 that this change in behaviour occurs as the tanδ curve is rising towards its peak, that is as the material is approaching its glass transition temperature. So the transition from non-crack bridging to crack bridging behaviour occurs in the temperature range associated with the glass transition. This relationship is seen again in the discussion of the crack accommodating results in Section 5.3. For a given thickness of coating a temperature will be reached after which the width of crack bridged will not increase any further. This is
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illustrated by the 0.2mm coating thickness data. The 0.4mm thick coating could be expected to exhibit this behaviour at a higher temperature than the 0.2mm thick material.

5.2.3. Large crack opening tests

When the results from the large crack opening tests, described in Section 3.10.6, are examined it can be seen that extensions of up to 12mm were observed, Table 4.5. As the cracks were formed in-situ, beneath the coatings, the original crack width can be assumed to have been zero as the substrate was originally continuous. In Section 5.2.1 it was postulated that there must be a mechanism by which the coating 'obtains' some free length which may be strained. When the free film specimens were tested the strains to failure ranged from 960% to 2032%, Section 4.4.2. If these strains to failure are applied to the large crack opening tests it is possible to calculate the debonded length of coating required to account for the extensions observed. If the strain to failure of the coating that extended to 12mm was 960% (the lowest failure strain from the free film tests) the debonded length of coating predicted is greater than 1.25mm, or 0.625mm on either edge of the crack, or failure would have occurred. This reasoning assumes that there is no difference in the behaviour of the coating when it is constrained on a substrate and when it acts as a free film. This argument is simplistic since in practice the substrate will provide lateral constraint whilst the free film exhibited significant narrowing when extended.

5.2.4. Conclusions from the discussion of crack bridging behaviour

It can be seen that temperature, coating thickness, debond/free film length and degradation due to weathering are important parameters when characterising the crack bridging performance of a coating material. For a given coating thickness, as the temperature is increased from the region in which crack bridging does not occur, the material will eventually begin to crack bridge. This can be compared with the ductile brittle transition that is seen to occur in the crack accommodation results, Section 5.3. As the temperature is increased further the material will be able to bridge wider cracks without failure. At some point a limiting crack width will be encountered which it will not be possible to exceed.
because the stress in the coating will be in excess of its strength. An increase in coating thickness will allow a wider crack to be bridged until the limiting crack width is reached for the increased thickness. Increasing exposure to weathering reduces the maximum crack width that can be bridged for a given set of conditions due to the degradation that this process causes, Section 2.5.4.

5.3. Crack accommodation

It can be seen that a material must be able to crack bridge in order for it to be able to crack accommodate but fulfilling this requirement alone will not guarantee crack accommodation. The ability of a particular coating material to bridge cracks has been shown to be related to coating thickness, temperature, crack width and level of weathering. This is sufficient characterisation only when the crack is passive i.e. not moving. Crack accommodation data is also necessary to ensure a durable protective coating when the crack is active. Crack accommodation behaviour will vary depending on:

i/ the material,

ii/ coating thickness,

iii/ degree of weathering,

iv/ temperature.

**i/ material type**

An elastic material will strain as the crack is opened and then when the crack closes the strain will be recovered and the material will be as it was before the crack was opened, Figure 5.10. Figure 5.11 shows the theoretical relationship between crack opening and coating stress. The response of an ideal elastic material to an applied stress was shown in Figure 2.14.
Figure 5.10. Elastic coating over a crack

Figure 5.11. Response of an elastic coating to crack movement
A viscous material will strain as the crack opens but there will be no elastic restoring force to make it contract again. The response of an ideal viscous material to an applied stress was shown in Figure 2.15. The material may be compressed as the crack closes in which case it will be deformed again but it is unlikely to flow back to its original shape, Figure 5.12. Figures 5.13a and 5.13b show the theoretical relationship between crack opening and coating stress for such a material. Two cases can be described, case (a) where the time that the crack takes to open is greater than the relaxation time for the material and case (b) where the time that the crack takes to open is less than the relaxation time. Case (a) allows no opportunity for stress to develop in the coating. This means that the coating is under little or no stress anywhere in the crack opening cycle, Figure 5.13a. Conversely, case (b) does not allow complete relaxation while the crack is opening. However, if we assume perfect dashpot behaviour any stress present must fall to zero the instant the crack stops moving. When the crack is closing the stress in the coating is reversed, Figure 5.13b. Alternatively the coating could go into compression or buckle when the crack closes.

If the coating material is viscoelastic in nature it can undergo both elastic and time dependant deformations when the crack is opened. The stress in the coating can be complex and the time for which the crack is open compared to the relaxation time of the material is again an important factor. Some relaxation can occur while the crack is open but some of this may be recovered while the crack is closed. The levels of relaxation and recovery that occur will vary with the relaxation time, the time that the crack is open and the stress in the coating. This means that when the crack closes the elastic deformation will be recovered almost immediately whereas the time dependant deformation will be recovered more slowly, if indeed it is recovered at all. This may lead to the situation where the stress in the coating on subsequent cycles is lower. At some point the stress in the coating could fall to such a level that stress relaxation no longer takes place. The stress in the coating on each subsequent cycle will now be the same due to the deformations now being only elastic in nature, Figure 5.14. If sufficient relaxation has taken place the coating may be 'slack' when the crack is closed and this would give the coating the appearance of a fold in a bellows, Figure 5.15.
Figure 5.12. Viscous coating over a crack

Figure 5.13a. Response of a viscous coating whose relaxation time is less than the time for which the crack is open
Figure 5.13b. Response of a viscous coating whose relaxation time is greater than that for which the crack is open

5.14. Response of a coating that creeps and reaches an equilibrium stress
**ii/ coating thickness**

The maximum crack width that can be bridged is the limit on the maximum crack that can be accommodated. As the coating thickness is increased, the crack width that can be bridged will increase, and so the crack movement that can be accommodated is also likely to increase. This means that an increase in fatigue life could be accomplished by increasing the coating thickness, which increases the maximum crack width that can be bridged, or by decreasing the crack width to be accommodated.

**iii/ level of weathering**

As the level of weathering is increased, the amount of degradation of the coating will increase. This will lead to reduced ductility and a reduced fatigue life.

**iv/ temperature**

The temperature of the coating will effect its behaviour. This was demonstrated in the discussion of the crack bridging results in Section 5.2.2. If the material is unable to crack bridge at a particular temperature due to it exhibiting brittle behaviour it will be unable to...
accommodate repeated crack movements. A detailed discussion of the effect of temperature on crack accommodating ability is presented in Section 5.3.1.

In order to show the relevance of these factors to crack accommodating behaviour it is necessary to examine the data obtained from crack accommodating tests.

5.3.1. Crack accommodating lifetime, material C

The results of the test carried out on un-weathered material C1 are shown in Figure 5.16. It can be seen that there are two distinct levels of crack accommodating behaviour evident in the results. Looking at the results for the un-weathered material there is a region up to and including -10°C where there is no crack accommodation. There was also no crack bridging with this material at -20°C, Section 5.2.2.3. However, at -3°C and above the coating is capable of accommodating crack movements of several thousand cycles. This suggests that somewhere in the region from -10°C to -3°C the behaviour of the coating material changes from being brittle to being ductile. This behaviour can be represented in graphical form by three regions as shown in Figure 5.17.

![Figure 5.16. Fatigue lifetime for material C1](image-url)
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Figure 5.17. Graphical representation of the three regions of fatigue behaviour for material C1.

Figure 5.18. Fatigue lifetime for artificially weathered material C1.
It is not possible to say whether the transition in the region -10°C to -3°C is a sudden step or a slope. The glass transition occurs over a range of temperatures and has already started by -10°C. As the glass transition is not a discrete change in properties the transition to crack accommodating behaviour may be expected to occur over a range of temperature as well. To characterise this transition precisely it would be necessary to carry out several tests over this 7°C range of temperature. Further tests on artificially weathered material C1 allow a more detailed understanding of this region, Figure 5.18.

The weathered material also shows this change in behaviour, Figure 5.18. In this case however, the material survives for less than 10 cycles at -3°C whereas the un-weathered material survived several thousand cycles at this temperature. At 0°C the material is showing fatigue lives ranging from 0.5 cycles to approximately 10000 cycles which is similar to that of the material at 20°C. So it appears that the ductile/brittle transition in the case of the weathered material is not a sudden step but a region of high variability. Thus in this region it is not possible to accurately predict the fatigue life of the coating material. This behaviour is not surprising since the glass transition occurs over a range of temperature and not at one discrete point. This is illustrated in Figure 5.19.

![Figure 5.19. Fatigue lifetime and tanδ curve for artificially weathered material C1](image-url)
It must be remembered that the glass transition temperature has been defined as the temperature at which maximum mechanical damping occurs, although the change from glassy to rubbery behaviour occurs over a range of temperature, in this case between approximately -20°C and 20°C. It seems reasonable then that there is some scatter in the results within this region as the distribution of molecular conformation in the coating material are changing with temperature. At 0°C, even though it may crack-bridge, this material would be unsuitable for use as a protective coating as it is not possible to predict whether the coating will fail at 0.5 cycles or 10000 cycles due to the variability in the crack accommodation data. The scatter at 20°C is acceptable however as the lowest fatigue life at this temperature is 3410. 3410 cycles is predicted to give a usable service life of 9.3 years on a real structure assuming one cycle of movement every day. This will be discussed in Section 5.3.7. As with the un-weathered material it would be necessary to carry out more experiments to precisely define the upper and lower limits of this ductile/brittle transition. It is important to note that from a practical engineering perspective it is more important to have as little variation as possible rather than a very high fatigue life.

![Figure 5.20. Fatigue lifetime for un-weathered and weathered material C1](image)

Figure 5.20. Fatigue lifetime for un-weathered and weathered material C1
The difference in the performance of the un-weathered and weathered material is shown in Figure 5.20. As the coating formulation and all application and testing conditions were the same for the two test series, any differences in behaviour can be attributed to the artificial weathering. It can be seen from Figure 5.20 that material C1 has passed its region of variability at -3°C while material C1QUV is still showing variability at 0°C. When the glass transition temperature was measured for material C1QUV it was found to be 1.5°C lower than that of the un-weathered material. The average number of cycles to failure above the ductile/brittle transition is similar for both material C1 (5437) and material C1QUV (5659). This suggests that for this material 500 light hours artificial weathering does not significantly affect the overall fatigue life once the ductile/brittle transition has been passed, but does affect where this transition occurs.

Results from the tests carried out on material C2 show the effect of both weathering and crack opening on crack accommodating performance at -15°C, Figure 5.21. The material survived only 1300 cycles when subjected to a crack opening of 0.2 - 0.4mm. When the crack opening was reduced to 0.07 to 0.29mm the coating was able to accommodate over 10000 cycles of crack movement. With this material we can see the effect of weathering at three different exposures 0, 500 and 3000 hours. Increasing exposure leads to a slight reduction in crack accommodating ability at both 500 and 3000 hours exposure.

5.3.2. Crack accommodating lifetime, material D

Figures 5.22 and 5.23 show the crack accommodation results for material D1 and material D2 respectively. According to the supplier the formulation of material D2 was modified from that of material D1 to aid low temperature application.

The D1 material shows zero crack accommodating ability at -30°C. At -20°C the material exhibits three results of zero crack accommodating ability and one failure at 277 cycles. This can be compared to material C1QUV at 0°C where this type of scatter was also evident, Figure 5.18.
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Figure 5.21. Effect of weathering on the crack accommodating ability of material C2 at -15 °C.

Figure 5.22. Fatigue lifetime for material D1.
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At temperatures greater than -10°C failure occurs in the region of 5419 to 24145 cycles. At 20°C the variability is such that it would not effect the use of the coating on a real structure as the lowest fatigue life (5419) would give a lifetime of 14.8 years allowing one cycle for each day. The transition to crack accommodating behaviour for this material has already started at -20°C but would be unusable below -10°C because the variation in behaviour at these temperatures means that it is possible for it to fail after a very low number of cycles.

Material D2 exhibits no crack bridging ability up to and including -20°C. It does not show the variability seen in material D1 at -20°C. At temperatures of -10°C and above the material does show some variability with failures ranging from 2134 to greater than 30951. It is possible to say that the transition in behaviour takes place between -20°C and -10°C and as a consequence this material would be unusable below -10°C as was the case with material D1. At 0°C material D2 showed some variability, with one failure at 12943 cycles while the two other specimens reached 10802 and 30951 cycles with little apparent damage and therefore no failure. This shows that the coating is capable of sustaining higher fatigue lives at 0°C than it can at 20°C so increasing the temperature does not necessarily guarantee increased fatigue life. The lowest fatigue life would give a lifetime of 5.8 years so this variability would not affect use of the coating for many engineering applications.

The two coating materials are more easily compared if both sets of results are presented on the same axes, Figure 5.24. The results for material D1 and material D2 show similar behaviour. The change in formulation has given rise to little change in the overall fatigue behaviour of the material. The failures in material D1 coating at 20°C and -10°C are fairly consistent and of the same order of magnitude, that is between an average of 11165 and 13665 cycles respectively. Material D2 deviates from this pattern at 0°C. The failures at -10°C and 20°C are in reasonable agreement with the averages of 6198 and 3993 respectively. Given that the glass transition temperatures for material D1 and material D2 are -5.5°C and -7°C respectively it would be expected that the materials behave in a similar manner. This is further evidence that the test method gives reproducible results.
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Figure 5.23. Fatigue lifetime for material D2

Figure 5.24. Fatigue lifetimes for material D1 and material D2
Figure 5.25 shows the results from the crack accommodating tests on the artificially weathered material D2. It can be seen that for temperatures up to and including -18°C material D2QUV shows zero crack bridging ability. At -10°C the results show scatter between 151 and 1314 cycles. This is comparable to the scatter in the results for material C1QUV at 0°C discussed in Section 5.3.1. At 0°C the material fails at 20172 cycles and at 24°C and 25°C no failures were observed after the coating had been subjected to between 43360 and 50773 cycles. In the case of material C1QUV the artificial weathering increased the temperature at which crack accommodating occurs reliably but does not significantly influence the crack accommodating lifetime once reliable crack accommodating behaviour has begun. Although the artificially weathered material D2 also showed an increase in temperature at which reliable crack accommodating behaviour started, this time there was an influence on the behaviour at the higher test temperature. The artificially weathered material showed an increase in performance over the un-weathered material.

In order to compare these results with those from the un-weathered material D2 the two sets of results are presented on the same axes, Figure 5.26. At temperatures below -18°C both
materials show zero crack accommodating ability. At -10°C the performance of the weathered material has been degraded when compared to the un-weathered material. The weathered material exhibits fatigue lives of between 151 and 1314 cycles whereas the un-weathered material exhibits fatigue lives of between 4432 and 8522 cycles. The crack accommodation data for the material D2 and material D2QUV at 0°C are similar and show adequate performance. At 20°C material D2 showed failures at an average of 3993 cycles, ranging from 2134 cycles to 14589 cycles. Material D2QUV gave two results at 24°C and one at 25 °C of 43360, 50481 and 50773 cycles without failing which shows an increase in performance after artificial weathering. It is unlikely that this large difference in crack accommodating behaviour could be due to a 5°C change in test temperature, or a 3.5°C difference in glass transition temperature. It is clear from the comparison of material D2 and material D2QUV results that the material could become un-serviceable at -10°C if the coating has suffered significant weathering in-situ due to the high variability in fatigue life. This means that the amount of weathering that the coated surface would be subjected to in use would have to be evaluated and not just the service temperature.

![Figure 5.26. Results from un-weathered and weathered material D2](image-url)
5.3.3. Model of crack accommodating results

There is no accepted model currently available to describe the crack accommodating ability of viscoelastic coatings and so the following model is proposed.

From the results of the crack accommodating tests already discussed it is evident that two distinct levels of crack accommodating behaviour occur and that the position of these regions is dependent upon the temperature of the coating material. Figure 5.27 shows these two levels of behaviour for a given material type, crack opening and coating thickness. At temperatures below the ductile/brittle transition the coating will fail on the first opening half cycle, region A, and fail to exhibit any crack bridging behaviour at all. At higher temperatures in the vicinity of the glass transition, the coating will be expected not to fail due to brittle fracture but to survive more than one half cycle as shown in region C. In this region the number of cycles to failure will depend on the ease with which defects can
initiate and propagate through the coating. The glass transition occurs across a range of temperature and so it is reasonable to expect a transition where the behaviour of the coating changes from brittle to ductile, rather than a discrete change. This is represented by region B and will be related in some way to the glass transition temperature.

Region A will be a horizontal line showing fatigue failures occurring on the first opening half cycle until region B is entered. This is due to the brittle behaviour of polymeric materials at temperatures below their glass transition temperature.

Region B has been shown to be an area of high variability in crack accommodating lifetime where it is not possible to estimate a reliable lifetime. A coating material could still be utilised in this area if the variability occurred below a satisfactory lower limit.

In region C however the fatigue lives may not give a horizontal line as in region A. There are two generic possibilities as to the shape depending on whether the properties of the coating are a function of temperature.

i) If the number of cycles to failure is not a function of temperature the line will be horizontal. If this is the case the processes that lead to crack initiation and propagation through the coating are not temperature dependent.

ii) If the number of cycles to failure is a function of temperature then the line will not be horizontal, but may have a positive or negative gradient.

Material C1 demonstrated a flat line in this region while material D2 has a negative gradient and material D2QUV has a positive gradient.

5.3.4. Ductile/brittle transition

All of the materials looked at have a characteristic glass transition temperature, Table 4.4. They also all have a range of temperatures during which the transition from brittle to ductile behaviour occurs. This is apparent from the graphs in Sections 5.3.1 and 5.3.2. Where the ends of these ductile/brittle transitions are not defined absolutely, they are defined as a range of temperatures which encompass the ends of the transition, Table 5.1. It is possible
to see when the transition to reliable ductile behaviour has occurred as the material shows a similar crack accommodating behaviour with increasing temperature. In order to get more precise data for the ends of the transition it would be necessary for further tests to be carried out at temperatures between those already evaluated.

<table>
<thead>
<tr>
<th>Material</th>
<th>Lower end (°C)</th>
<th>Upper end (°C)</th>
<th>Tg (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>C1</td>
<td>-10 to -3</td>
<td>-10 to -3</td>
<td>7</td>
</tr>
<tr>
<td>C1QUV</td>
<td>-20 to -3</td>
<td>0 to 20</td>
<td>5.5</td>
</tr>
<tr>
<td>D1</td>
<td>-20 to -10</td>
<td>-20 to -10</td>
<td>-5.5</td>
</tr>
<tr>
<td>D2</td>
<td>-20 to -10</td>
<td>-20 to -10</td>
<td>-7</td>
</tr>
<tr>
<td>D2QUV</td>
<td>-18 to -10</td>
<td>-10 to 0</td>
<td>-3.5</td>
</tr>
</tbody>
</table>

Table 5.1. Ductile/brittle transitions.

It has already been seen that the ductile/brittle transitions do not seem to coincide exactly with the glass transition temperatures of the coating materials although further fatigue testing at the glass transition temperature of each coating would clarify this. However, it is interesting to examine the possible locations of the tanδ curve in relation to the regions of behaviour in the model shown in Figure 5.27. Figure 5.28 shows five possible tanδ curves and the three regions of behaviour A, B and C. If the results of the crack accommodation evaluations on the C1 and D materials are examined it can be seen that with the exception of material D2QUV reliable crack accommodating behaviour has been achieved before the glass transition temperature has been reached. This means that the transition region B is taking place while the tanδ curve is rising towards maximum damping, i.e., approaching the glass transition temperature. This is depicted by curves 4 or 5 in Figure 5.28. It is possible that this is also the case with material D2QUV but that further tests between -10°C and -3.5°C would be necessary to show this. However, the crack accommodating data for material D2QUV suggest that the tanδ curve positioning could be that represented by curve 3 in Figure 5.28.

It is conceivable that any uncertainty in the ductile/brittle transition temperature could allow this transition to coincide with the glass transition thus allowing us to use glass transition temperature to define the ductile/brittle transition.
5.3.5. Failure modes in the crack accommodating coatings

The mode of failure for each coating type was different, the differences being the initial damage and the way that damage developed and propagated within the surface coating. With material C damage formed in the surface of the coating and had the appearance of a narrow light coloured channel, in several places, along the length of the crack, Figure 5.29. Pits where then seen to form along these lines, growing deeper as the fatigue test progressed. Eventually one of these pits penetrated the coating which was therefore said to have failed using the criteria stated in Section 3.4.1. During this type of failure the coating stretched and relaxed over the crack giving the appearance of being taut at both extremes of crack opening. This means that on each cycle the coating is strained as the crack opens, and relaxes to an extent sufficient to take up any 'slack' when the crack closes.
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Figure 5.29. Failure mode seen in type C materials

Figure 5.30. Failure mode seen in the type D materials
The failure mode for the type D materials was different to that for the type C materials in that the initial damage was roughly circular, shallow and formed at discrete sites along the crack and not along channels, Figure 5.30. This damage then coalesced along the crack to give larger areas of damage. The damage eventually propagated through the thickness of the coating but only after a large amount of the original shallow damage had coalesced. During the fatigue process, when the crack was open, the coating appeared taut. When the crack was closed the coating appeared loose giving the appearance of a fold in a bellows. This can occur when the deformation in the coating is not recovered during the period when the crack is closed, Section 5.3. This could be due to insufficient time for the relaxation to take place, or that the deformation is in fact non-recoverable, or a contribution of both of these. This would lead to bending at the hinges that form as the crack closes.

5.3.6. Rate dependency and notch sensitivity

The prior discussion has highlighted the importance of temperature on the crack accommodating ability of these coating materials. Other aspects of temperature related behaviour may be important when assessing crack accommodating ability. For example, in all of the tests carried out for this work the initial crack was initiated and grown at 20°C and not at the temperature at which the test was to be carried out. This procedure was adopted because at 20°C all of the coatings were above their glass transition temperature and this would limit any damage done to the coating when the crack was initiated. If the coating material becomes more notch sensitive with decreasing temperature then the coating could fail to bridge the initial crack even though it was capable of accommodating the same crack at that temperature. This could lead to crack accommodating data that is better than that which would have occurred if the substrate crack was formed at the temperature of the test where the test temperature was below 20°C.

Rate sensitivity is an important factor since the instantaneous stress on a viscoelastic material is normally much greater than the equilibrium stress, the stress being dependent upon the strain rate. This relationship was illustrated by Equation 2.8, reproduced below.
As the strain rate increases, so does the instantaneous stress. The rate at which the crack is opened when it initiates is unknown. There is a large amount of energy stored in the mortar substrate just prior to crack formation. When the crack does form this energy is released as the mortar relaxes. It is this relaxation that will lead to very fast crack openings when compared to the crack opening rates imposed by the testing machine. It is thought that at 20°C, when the material is behaving in a ductile manner that the effect of strain rate will be minimised.

5.3.7. A practical test to evaluate the crack bridging ability of coating materials on a commercial basis

One of the aims of this work was to develop a screening test for protective coatings for reinforced concrete. When coatings, and indeed many other products, are to be evaluated an accelerated test is often required. If the coating is expected to last for 10 years, for example, then testing in real time is not a practical proposition. By the time a material has been evaluated new materials may have been developed that out perform it. Further, any improvements would take another 10 years to evaluate. This type of accelerated testing can be seen in the methods of artificial weathering using high intensities of ultra-violet light, relatively high temperatures and high humidities. While there is a need for accelerated testing, the information required from the test is that the material can perform reliably at the crack openings for which it is being specified. For this reason then, tests of ultimate crack accommodating (and indeed crack bridging) ability are unnecessary. It is not necessary to know if a coating material can bridge a crack of 10mm when the design limit is 0.3mm. At a crack width of 10mm it is likely that the structure would have failed. Similarly, it is not necessary to know that a coating will accommodate a crack for 15000 cycles when it would only need to survive for 6000 cycles after which it may have failed due to ultra-violet degradation and would need to be replaced anyway. The large crack openings used for the evaluations in this work were of a size that would be caused by thermal expansion and not of the type that would be caused by traffic loading. This would suggest one crack
opening/closing cycle each day. A 6000 cycle test would give nearly 16.5 years of actual use at one cycle per day. Coatings would normally be expected to last for 5 to 10 years in order to be economically viable due to the cost of closing a structure and erecting scaffolding. This then is clearly in excess of what is required. A 6000 cycle test at 0.3 Hz also fits conveniently into a standard working day, taking little more than 5 hours to complete. This then provides a straightforward accelerated test that gives a pass/fail result at a given fatigue life requirement.
6. Conclusions

From the work undertaken it is possible to draw conclusions regarding the reliability and reproducibility of the test methodology and apparatus. Due to the nature of the test it has also been possible to examine the crack bridging and crack accommodation of viscoelastic coatings used on reinforced concrete.

The test methodology can be used to screen protective coatings for reinforced concrete structures in a pass/fail test by defining a minimum number of cycles, for a given set of conditions, that the coating must survive.

The test methodology can be used as a comparative test of the performance of protective coatings by establishing the crack accommodation lifetime of the coatings under test.

Detailed conclusions regarding the test method, crack bridging and crack accommodation behaviour are presented in the following sections.

6.1. Test methodology

The test methodology developed, including the machine, specimen, test method and interpretation of data, is able to fulfil the requirements set out in Chapter 1 for testing coatings on reinforced concrete structures.

The machine is be able to open a crack in the test specimen with a precision of ±2.9% over a period of 8000 cycles, Section 5.1.1.

The machine is able to reproduce a particular crack opening in several test specimens.

There was no correlation between variations in crack width and number of cycles to failure, Section 5.1.2.
The data for duplicate tests on one material type fall into well defined groups showing that the results are reproducible and comparable, section 5.1.3.

This shows that the methodology is suitable for the assessment of crack bridging and crack accommodation behaviour.

6.2. Crack bridging behaviour

A mechanism exists that allows some coating materials to extend over a crack formed in-situ, beneath the coating, without failure of the coating.

Temperature, coating thickness and degradation due to weathering are important parameters controlling crack bridging behaviour of coatings used on reinforced concrete structures.

For a given thickness of a particular coating material there is a temperature above which crack bridging is found to occur reliably. This temperature is related to the glass transition temperature of the material. The relationship is not clear cut. Above the glass transition temperature crack bridging occurs in all of the cases examined. As the test temperature is reduced below this temperature the ability of the coating to bridge the crack when it forms is reduced. If the temperature is reduced further a point is reached where the coating will cease to exhibit any crack bridging ability. This temperature is below the glass transition temperature.

For a given coating material, at any temperature at which crack bridging occurs, increasing the thickness of the coating increases the maximum crack opening that can be bridged.

For a given thickness of a particular coating material, at any temperature at which crack bridging occurs, increasing exposure to artificial weathering reduces the crack width that can be bridged.

Crack bridging is not observed in polymers exhibiting glassy behaviour.
6.3. Crack accommodating behaviour

Crack accommodation behaviour of viscoelastic coatings can be described using a model consisting of three regions defined by temperature, \( T \leq T_g \). In the lowest temperature region, (A), the coating material shows no crack accommodating ability, failing on the first opening half cycle.

As the temperature is increased, the next region, (B), in which the transition from non-crack accommodating to crack accommodating behaviour is encountered. In this region variability in crack accommodation lifetime at constant temperature was observed with some of the materials tested. This makes it impossible to accurately predict crack accommodation lifetimes.

As the temperature is increased further a final region, (C), is reached, where significant crack accommodation lifetimes occur.

The temperature at which crack accommodating behaviour occurs is related to the glass transition temperature of the coating. Above the glass transition temperature all of the materials tested exhibited reliable crack accommodating behaviour. As the test temperature was decreased below the glass transition temperature the likelihood of reliable crack accommodating behaviour is reduced.

The failure mode of the type C and type D coatings is different.

Artificial weathering affects the crack bridging ability of the materials in some regions of the model.

Region (A) appears to be un-affected by artificial weathering.

The crack accommodating behaviour in region (B) is affected in such a way as to reduce crack accommodating lifetimes at a given temperature and to increase the variability of the lifetimes.
Chapter 6: Conclusions

The effect on crack accommodating ability in region (C) depends upon the material under test. Considering material C1, the lower boundary of region (C) has been moved to a higher temperature with the consequent change in the position of the upper boundary of region (B). The glass transition temperature is also increased by artificial weathering. The crack accommodating lifetime at 20°C shows more variability for the weathered material than for the un-weathered material.

In the case of the artificially weathered material D2, crack accommodating performance is enhanced at the higher temperature end of region (C).

Crack accommodating ability is reduced at constant temperature as the level of artificial weathering is increased, material C2.

For a given material type a reduction in crack opening increases crack accommodating lifetime at constant temperature and coating thickness.
AFNOR T 30-702, 'Revetements Plastiques Epais Essai de Vieillissement Conventionnel', L'Association Francaise de Normalisation. 1976

Agreement Board, Certificate No. 69/32, for Swiftcrete Ultra High Early Strength Portland Cement. 14 April 1969


Biczok I, 'Concrete corrosion, concrete protection', Academiai Kiado, Budapest, 1972, p443.

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CIRIA Technical Note 130, 'Protection of reinforced concrete by surface treatments', Construction Industry Research Association, p18-20


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Macdonald M D, 'Waterproofing concrete bridge decks: materials and methods', TRRL Laboratory Report 636, Transport and Road Research Laboratory, Department of the Environment.


Price W H, Factors influencing concrete strength, Journal of the American Concrete Institute, 47, February 1951, p 417-432.


Verbeck, G J, 'Mechanisms of corrosion of steel in concrete', Corrosion of metals in concrete, SP-49, American Concrete Institute, Detroit, 1975, p21-38.


A. Fatigue machine design and construction

A summary of the fatigue machine design and constructional details was given in Section 3.2. The testing machine requirements were also listed there but are re-iterated here to aid reading this Appendix.

A.1. Testing machine requirements

The testing machine had to simulate as closely as possible the service conditions of a coating applied to an external structure. These requirements are listed below:

- cyclic test (tension-tension fatigue loading).
- dedicated testing machine
- reliable power source.
- reliable and straightforward to operate, that is, no complicated operating procedures that could result in inconsistencies and errors.
- testing at a variety of temperatures.
- testing at a variety frequencies.
- unattended operation.

When the design of the machine was initially considered with the above points in mind, a piston type linear actuator was decided upon. This would make the machine relatively straightforward to construct and operate. It gave the option of oil or air under pressure to operate the cylinder. The final choice was for a compressed air system. The reasons for this are:

- There was a possibility that the complete machine would have to be operated at low temperatures. Under these conditions the viscosity of oil can increase and alter the operating characteristics of the machine.
Appendix A: Fatigue machine design and construction

- Financial constraint. There was already access to a compressed air main in the laboratory which could be backed up with a portable compressor in the case of mains failure. In contrast the power pack for providing oil under pressure would be relatively expensive.

- Previous experience had demonstrated the feasibility of this approach.

A.2. Selection of compressed air cylinder and lever

The main criterion considered when deciding on the cylinder dimensions was that the machine was required to be able to exceed the ultimate tensile strength of the specimen reinforcing bar. This would then allow any plastic deformation of the bar required by a test to be achieved.

The yield strength of the reinforcing steel used is 250MPa. With a 7.94mm (5/16 inch) diameter bar a load of 12379 Newtons is required to exceed this strength. This means that the system would have to be capable of exerting a force of at least 12379 Newtons on the reinforcing bar. Having decided on a piston type actuator the next consideration was how to apply the force generated by such a device to the reinforcing bar in the specimen. It was decided to use a lever. The advantages of the lever are:

- it allows the use of a smaller cylinder due to the mechanical advantage provided by the lever.
- it reduces the height of the machine by allowing the cylinder to be placed alongside the specimen instead of in line with it, Figure 3.4.

The length of lever was 500mm, Figures A1 to A3. This was to allow sufficient room between the cylinder and specimen for a temperature cabinet. The pressure in the compressed air main varies from 0.690MPa to 1.034MPa (100 psi to 150 psi), so the maximum continuously available air pressure is 0.690MPa (100 psi). It was decided to select the cylinder to work on a maximum of 0.483MPa (70 psi) so that there was a minimum of 0.207MPa (30 psi) available in reserve.
There are also some disadvantages to the use of a lever. These are:

- The pivot points associated with the lever lead to increased friction in the system. This could cause a problem as the cylinder is only driven in the loading direction. Any additional friction could lead to the crack not closing sufficiently at the end of each cycle. Due to the loads experienced by the pivots it was decided to use needle roller bearings at these points. This leads to increased complexity and possible reliability problems.

- The use of a lever increases the horizontal span of the reaction frame and so to keep deflections of the machine to a minimum a heavier section of universal beam would have to be employed.

On examining cylinder manufacturers data it was seen that a cylinder with a bore of 152.4mm (6 inches) would be capable of producing a force of 6000 Newtons with an air pressure of 0.483 (70 psi). If this were transmitted through a lever with a 1:4 mechanical advantage it would provide a force of 24000 Newtons at the specimen reinforcing bar. This is nearly double the 12378 Newtons required to exceed the ultimate tensile strength of the reinforcing bar. This extra capacity allows the machine to operate well within its limits and ensures that any minor changes in bar size or composition can be accommodated. The cylinder chosen was a Martonair M960, Figure A4. The cylinder is attached to the lever by a crosshead, Figure A5.

A.3. Control of the cylinder: valve selection

The operation and control of the pneumatic cylinder was achieved by a two position, solenoid actuated valve. The valve connects the compressed air supply to one cylinder port with the result that the piston moves away from that port and towards the other. The valve also connects the remaining cylinder port to the exhaust pipe so that air trapped behind the piston can be vented to atmosphere (through a silencer). The valve was capable of swapping the air supply and exhaust pipes so that the cylinder can be moved in both directions. This makes electronic control of the valve possible. Once the valve is in the required position it will stay there until the other solenoid is energised. A full description of the operation of the testing machine is given in Section 3.3.
Appendix A: Fatigue machine design and construction

A.4. Control of valve position: timing circuit

The requirements for the valve timing circuit are:

- independent control of the time that the valve and hence the cylinder is in either position.
- the valve must be able to be held in either position for specimen loading and examination of a specimen during a test.

The first condition is fulfilled by the use of an asymmetric timer. This is a timing circuit with change over contacts. The time that each set of contacts are closed can be varied independently. With each set of contacts operating one solenoid, asymmetric timing control of the valve position is accomplished.

The valve is operated through two 12V ac solenoids. The timer and solenoids are powered by an unregulated 12Vac mains operated power supply. The circuit is protected by a 1 amp fuse. A counter is connected to one of the solenoids and registers the number of times the cylinder completes one loading/unloading cycle. The circuit is shown in Figure A6.

A.5. Variation of the load applied by the cylinder

The load applied by the cylinder is varied by changing the pressure of the air supplied to it. This is achieved by passing the air through a regulator unit which can vary the air pressure from zero to the supply pressure and maintain it at a constant level when the supply pressure fluctuates. The air pressure in the machine is monitored by a 0-1.379MPa (0-200 psi) Budenburg 254mm (10 inch) standard test gauge. It was decided to fit a valve to isolate the pressure gauge from the air supply when the machine is operating to prevent it being damaged by the shocks induced by the sudden changes in air pressure as the piston changed position.

A.6. Specimen grips

As already described in Section 3.1.3 the specimen terminates in a 7.9mm (5/16) diameter bar at each end. It was decided that the most reliable way to grip the bars was to use pre-stressing collets and barrels. The collets consist of a three part cone which grips the bar and
fits into a barrel with an internal taper corresponding to the external taper of the cone. The
assembly is tightened by applying a tensile force to the bar and barrel which has the effect of
drawing the collet into the barrel where the taper tightens the collet onto the bar. The action
is much the same as that of self tightening wedge grips used in tensile testing machines.

The grip itself consists of a cylindrical steel section with an integral crosshead (to fit the
lever) at one end. The top and bottom grips, Figures A7(a) and A7(b) respectively, are of
similar design although the top grip is longer and has an internal register to aid location of the
barrel. The grips have a hole bored into them from the crosshead end that is a clearance fit
for the barrel. A slot in the side of the grip below the crosshead allows the barrel to be
inserted into and removed from the grip. Both grips are able to pivot on their locating pins to
allow for any misalignment in the specimen/grips and to allow for the movement of the lever
(as the lever is pivoted it moves in an arc and so the top grip moves horizontally as well as
vertically).

A.7. Temperature control of the testing environment

During testing the specimen is surrounded by an Instron temperature cabinet, Figure A8.
This allows the temperature of the specimen to be held anywhere in the range of -70°C to
200°C. The coolant used is liquid carbon dioxide and heating is carried out using an electric
heater. The cabinet has an internal re-circulating fan and thermostat with an accuracy of ±1°C.

The temperature of the specimen is monitored by a Fluke digital thermometer using two type
K thermocouples, one inside the crack inducer hole (in contact with the mortar*) and the other
in hanging free in the cabinet. This allows the temperature of both the cabinet atmosphere
and the specimen to be monitored. If the mortar at the depth of the crack inducer is at the
cabinet atmospheric temperature, then the coating is also at that temperature.

A.8. Description of reaction frame.

The reaction frame, Figure A9 was made from 164mm by 155mm section universal beam,
Figure A10 and A11. This was the heaviest section available in this size (37kg/m). It was
designed to give the smallest deflection while keeping to a reasonable size of beam. The
beams are joined at the corners of the frame by welding steel plates, Figure A12 to the ends
Appendix A: Fatigue machine design and construction

of the flanges and webs of the vertical members and then bolting through these to the flanges on the horizontal members Figure A13. The height and width of the frame was chosen so that there was enough clearance around the lower grip, the lever and the bottom of the cylinder to allow room for brackets for fixing these items to the frame, Figure A14 to A22. It follows then that these brackets were designed after the frame had been built. All three brackets have four bolts fixing them to the frame. The grips, lever pivot and crosshead are located by 22.23mm (7/8 inch) hardened silver steel pins, Figure A23 to A25 that run directly in the steel of the bracket. Where the three pins pass through the lever they run in roller bearings pressed into the lever. The compressed air circuit was completed using 10mm copper pipe and brass compression fittings.

In order to provide good visibility at the testing surface, the machine was mounted on a concrete plinth to enable a stereo microscope to be supported at eye level when standing. This allows the film integrity to be easily examined at any time during the test. The mass of the plinth also provides vibration isolation from the surrounding laboratory.

A.9. Calculations for reaction frame.

It was desirable to make the top member of the frame as stiff as reasonably possible in order to reduce the amount of movement the cylinder had to make for each cycle. The section of beam required was calculated so that if it were simply supported it would deflect a maximum of 0.2mm when the reinforcing bar was under the design tension of 24000N, Gere and Timoshenko. As the beam was constrained at its end the actual deflection would be less than this in practice. The section chosen was 152mm x 152mm which weighed 37kg/m. A small amount of deflection in the frame would reduce the shock to the equipment when the load was applied.

A.10. Crack width measurement

To enable the crack width to be set and monitored, Linear Variable Differential Transformers (LVDTs) were used. The LVDTs had a stroke of 10mm and were set up to give zero volts at the centre of their stroke, +10 volts at +2.5mm and -10 volts at -2.5mm. This gives a theoretical accuracy of 0.025%. These were fixed to the edges of the specimen using purpose
made clamps and adjusters, Figure A26 (a) and (b), across the crack and in the plane of the coating, Figure A27. In order to attach the LVDTs, the side faces of the prism, where the LVDT mounts were attached, are now abraded with 240 grade emery paper to within 5mm of the coated surface (to avoid damaging the coating). The shot blasted and degreased LVDT mounts were then attached to the prism by applying Plastic Padding (Rigid) to one edge and then placing them on the abraded surface of the prism. The gauge length was defined by a setting tool which fits over both of the mounting blocks and so fixes their relative position. The LVDT's were powered by their own power supply/amplifier unit. The outputs from the amplifiers were fed to a data logging system. The data logger was calibrated and shown to give readings of LVDT movement with an accuracy of 0.01 mm. The logging rate was adjustable and two values were used, the first of 1 reading per second and the second of 20 readings per second. The lower rate was used for general test monitoring while the higher rate was used for the procedure outlined in Section 3.10.1, Waveform of crack opening. The data logger was controlled, and data displayed, by an IBM PS/2 Model 30 computer. The raw data was downloaded from the data logger memory at the end of each test onto floppy disks as Lotus .prn files so that it could be transferred to another computer for analysis using the Microsoft Excel spreadsheet package.
Figure A1. Lever part a
Appendix A: Fatigue machine design and construction

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Figure A2. Lever part b
Figure A3. Lever assembly
Appendix A: Fatigue machine design and construction

Figure A4. M960 pneumatic cylinder
Appendix A: Fatigue machine design and construction

Brian H Le Page
Item: Piston Rod Crosshead
Material: Mild Steel
Quantity: 1 off
Not to Scale
All Dimensions in Millimetres

Figure A5. Piston rod crosshead
Figure A6. Circuit diagram for controller
Appendix A: Fatigue machine design and construction

Figure A7(a). Top grip.
Figure A7(b). Bottom grip.
Appendix A: Fatigue machine design and construction

Figure A8. Intron temperature cabinet
### Appendix A: Fatigue machine design and construction

**Item:** Reaction Frame Assembly  
**Material:** Steel Universal Joist  
**Quantity:** 1 off  
**Not to Scale**  
**All Dimensions in Millimetres**

![Figure A9. Reaction frame](image)

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154
Figure A10a. Reaction frame top beam
Figure A10b. Reaction frame lower beam
Figure A11. Reaction frame vertical beam
Appendix A: Fatigue machine design and construction

Figure A12. Steel plate for welding to vertical beam end
Appendix A: Fatigue machine design and construction

Figure A13. Method used to join reaction frame members
Appendix A: Fatigue machine design and construction

**Item: Lower Pivot part a**

**Material:** Mild Steel

**Quantity:** 1 off

Not to Scale

**All Dimensions in Millimetres**

![Diagram of Lower Pivot part a](image)

---

**Figure A14. Lower pivot part a**
Appendix A: Fatigue machine design and construction

Figure A15. Lower pivot part b
Appendix A: Fatigue machine design and construction

Figure A16. Lower pivot assembly
Appendix A: Fatigue machine design and construction

Brian H Le Page

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Figure A17. Lever pivot part a
Appendix A: Fatigue machine design and construction

Brian H Le Page

Item: Pivot pt.b
Material: Mild Steel
Quantity: 1 off
Not to Scale
All Dimensions in Millimetres

Figure A18. Lever pivot part b
Figure A19. Lever pivot assembly
Appendix A: Fatigue machine design and construction

Figure A20. Cylinder support part a
Appendix A: Fatigue machine design and construction

Brian H Le Page
Item: Cylinder Support pt.b
Material: Mild Steel
Quantity: 1 off
Not to Scale
All Dimensions in Millimetres

Figure A21. Cylinder support part b
### Appendix A: Fatigue machine design and construction

**Item:** Cylinder Support Assembly  
**Material:** Mild Steel  
**Quantity:** 1 off  
**Not to Scale**

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**Figure A22.** Cylinder support assembly
Appendix A: Fatigue machine design and construction

Brian H Le Page

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<td>Quantity</td>
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Not to Scale

All Dimensions in Millimetres

Figure A23. Grip pin

Figure A23. Grip pin
Appendix A: Fatigue machine design and construction

Brian H Le Page

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Figure A24. Lever pivot pin

Figure A24. Lever pivot pin
Appendix A: Fatigue machine design and construction

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<td><strong>All Dimensions in Millimetres</strong></td>
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**Figure A25. Crosshead pin**

- Ø22.225
- M6 by 15mm deep both ends
- 750
Figure A26a. Linear variable differential transformer clamp
Appendix A: Fatigue machine design and construction

**Figure A26b. Linear variable differential transformer adjuster**
Figure A27. Positioning of LVDT's on specimen
B. Material names

Throughout this work the materials tested have been given a letter to identify them. Where two materials from the same manufacturer were tested a number was added as a suffix to the identification letter. Details of the materials can be found in this appendix. As these coatings are commercial products the manufacturers were reluctant to release information concerning the formulation. Only the limited descriptions below were available.

B.1 Material A

Manufacturer: Unknown

Description: bituminous

B.2 Material B

Manufacturer: Unknown

Description: tar extended epoxy

This material has been specified for use on reinforced concrete pipes segments

B.3 Material C

Manufacturer: Sika Inertol.

Name: Icosit Elastic.

Description: ethylene-copolymer based elastic dispersion.

This material forms part of the Icoment Concrete Repair System. Two batches were used in this work. The first batch was designated material C1 (supplied February 1989) and the second batch material C2 (supplied August 1992).
B.4 Material D

Manufacturer: Fosroc CCD Limited.

Name: Nitocote Dekguard Elastic Topcoat.

Description: elastic acrylate polymer.

Two batches of material were used in this work. The first batch was designated material D1 (supplied March 1990) and the second batch material D2 (supplied June 1991). The formulation of the second batch has been modified to aid low temperature application.