Durability Assessment of Sandwich Panel Construction

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Preface

The work presented in this study was done during the years 2001 – 2005 and submitted to the University of Surrey in August 2005.

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Finally the most warm thanks to Mrs. Susanne Gellweiler and my family for their support and patience during all the years of work.
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Dipl.-Ing. Lars Pfeiffer

Supervisor: Prof. Dr. D. Robert Griffiths (University of Surrey)
Co-supervisor: Prof. Dr. Klaus Berner (Fachhochschule Mainz)

Abstract:

The aim of this research is to establish a testing scenario, allowing an evaluation of the durability for sandwich panels. In the context of this research, sandwich panels are thin, metal-faced, three-layer panels with rigid core materials. A literature review has been carried out, highlighting the fact that, up to now, only limited research in the area of sandwich durability has been conducted. The research carried out up to date tried to distinguish between suitable and unsuitable materials for sandwich applications. This report tries to take a more accurate, quantity-driven approach, which includes the consequences of material property deterioration on design procedures. In a first introduction, the principle mechanical behaviour of sandwich structures together with the specific failure modes is presented. Different typical components and their basic properties are described. An introduction to the current state of the art with reference to the actual standards and regulations is given. Different aspects of durability impacts are shown. The shortcomings of durability evaluation in the current state of the art are presented and a plan of action to overcome the shortcomings is given. This includes the development of a mathematical model, connecting tensile strength perpendicular to the faces with wrinkling strength.

For polyurethane core panels, chemical reactions based on auto-oxidation under the presence of oxygen and diffusion models for oxygen into polymer matrixes are presented. An artificial ageing scenario is derived. Measurements from internal climates in mineral wool panels are combined with an existing ageing model. On the base of the obtained results, the ageing models presented in prEN 14509, the European standard for sandwich panels, are discussed. Finally, a complete testing and evaluation scenario, accessing sandwich durability, is proposed.
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Abbreviations and Symbols

The following symbols and abbreviations are used in this text
For a more detailed explanation refer to text

A  cross-section area
a  absorbency width, half wave length
B  overall width of the panel, flexural rigidity
b  width, length
C  capacity, constant value, carbon
c  bedding stiffness
D  diffusion constant, stiffness of face
d  depth, discontinuity
E  modulus of elasticity
e  distance between centroids of faces, base of natural logarithms (e = 2,718282)
F  force, load, constant value
f  function of, strength, deflection
G  shear modulus
H  hydrogen
I  radiation
k  coefficient, decaying index
l  length
M  bending moment, temperature-related material constant
N  humidity-related material constant, nitrogen
n  ageing rate coefficient, plain force per width
O  oxygen
P  possibility
p  partial gas pressure
Q  activating energy
R  resistance, reflectivity, moiety [chem.], gas constant
r  radius
S  effect of an action
T  temperature
t  time, thickness of face sheet
u  frequency of occurrence
v  vertical coordinate
w  deflection, deformation of face
xyz coordinates
α heat transition rate
γ partial safety factor, angle
Δ difference
ε strain
μ Poisson’s ratio
ξ diffusion factor
π potential energy
σ stress
φ angle
τ shear stress

Subscripts
A absorption
a outer (from German “aussen”)
B bending, latitude
C core
c compression, characteristic value
D durability (including long term degradation)
d design value
def deformation
E modulus of elasticity
e external
eff effective
F face
f variable action, face
G degree
i index, ideal
k convective
m mean
max maximum
p phase
R remaining (e.g. after exposure to artificial climate)
S sandwich panel
s radiation (from German “Strahlung”)
SC small scale (meaning down scaled test setup)
T temperature
t time, tension
u ultimate
v shear
w wrinkling
6P six point (bending test)
0 initial, basic
1 face 1 (outer face)
2 face 2 (inner face)

Abbreviations
DUR DURability test as described in prEN 14509
OSB Oriented Strand Board
PET PolyEThylene
PF Phenolic Foam
PIR PolyIsocyanuRate foam
PMMA PolyMethyl MethAcrylate
PUR rigid PolyURethane foam
PVC PolyVinylChloride
MW Mineral Wool
MWG Mineral Glass Wool
EPS Expanded PolyStyrene foam
RH Relative Humidity
XPS eXtruded PolyStyrene
1 Introduction

1.1 Sandwich panel construction

Building with factory engineered sandwich panels, consisting of a thick low density core between two thin high density faces, has become increasingly important in the construction industry over the last two decades. This is particularly true for panels with thin metal faces and a rigid core, providing good thermal insulation values. Sandwich panels are often used as lightweight wall cladding and roof finishes in industrial and commercial buildings (73% of all applications according to Koschade, 2002). Here, all advantages of a sandwich panel can be exploited. The metal faces provide a ready finish, both on the outer face, where they present the building envelope, as well as on the inner side. Such ready-for-purpose surfaces are efficient as mounting and fixing of panels becomes extremely time-effective because no additional finishing is needed. A high degree of prefabrication ensures minimization of on site related construction errors. Today about 80 million square meters of sandwich panels are produced and installed in Europe. This represents about 10 to 15% of the thin wall steel profile market. The biggest markets can be found in Germany, Italy, France and Great Britain (Koschade, 2002). All elements of a sandwich panel cross-section contribute to the mechanical strength of the system. In particular, the core combines thermal insulation skills with load-carrying abilities. The core takes shear stresses and provides bedding support for the faces. This fact, however, requires an awareness of special statics and design aspects as, for example, sufficient bonding strength between the individual layers. At the same time, sandwich panels are lightweight products, making them easy to handle and putting a minimum of dead load on the supporting structure. The principles of sandwich panel load-bearing behaviour and its regulatory background is described in this introduction.

1.1.1 “Sandwich panel” definition

Sandwich panels are composite materials, consisting of a minimum of two deck layers and a core. The term “panel” is derived from the Latin, French and Dutch word “paneel” and means “a flat piece of construction” (Brockhaus, 1991, a). This describes the general shape of a sandwich panel. The word “sandwich” goes back to the 4th Earl of Sandwich and generally describes a combination of different layers (Brockhaus, 1991, b). A typical sandwich layer in construction consists of three layers. A rather thick rigid core material is laminated between two thin faces. There are many possible combinations of facing and core materials, depending
on the intended use of the sandwich panel. This work, however, deals primarily with what is currently the most common form of sandwich panel in building construction: factory engineered elements, consisting of metallic facings and rigid foam or organic wool core.

1.1.2 Load-bearing behaviour

Generally, the sandwich panel consists of a minimum of three different layers: the two facings and a core. The individual layers by themselves have almost no load-bearing capacity. In a sandwich panel the layers no longer act separately but are connected in a process of adhesion. Only this rigid connection makes the panel a sandwich panel and increases the load-bearing capacity tremendously.

While the metal sheet facing on its own is almost without bending-capacity as is the core by itself, the rigid connection of the three layers creates a completely new composite structure with widely enhanced bending capacities. The composite sandwich panel possesses substantially greater load-bearing capacities with regard to bending and torsion impact than the sum of its individual components.

![fig. 1-1 metal faces of a sandwich panel by themselves (left) and sandwich structure with faces bonded to rigid insulating core (right)](image)

The reason for this effect is the division of the shear loads. Compared to the metal faces, the core in a sandwich panel generally possesses very little tension or compression stiffness. Almost the whole bending moment is therefore distributed to the two facing membranes. For a single span, three-layer sandwich panel under an equally distributed load, this leads to compression and tension in the two faces that are kept apart at a fixed distance by the core. Compared to the thin metal membrane layers, the core is relatively stiff in shear. The core, therefore, supports almost all of the shear force. Additionally, the core provides bedding for the sandwich panel faces. Because of that, the properties of the core have a significant influence on the overall performance of the sandwich panel and need to be carefully evaluated in sandwich panel design. Losses in stiffness and strength of the core have
Immediate influence on the performance of the whole panel. Such losses can, for example, be caused by durability-related degradation.

1.2 Introduction to durability aspects

A survey by Sarja (2002) on the typical share of civil engineering products for European counties shows that:
- Civil engineering products represent about 70 to 80% of the national assets.
- The energy use for these products during production and maintenance is about 40% of the total national energy consumption.
- Civil engineering products produce about 35% of the total waste.

These figures emphasise the enormous economical importance of civil engineering products for society. Due to the importance and costs of these products, it becomes obvious that there are high demands for service ability in life span or duration and functionality of these investments. Civil engineering products must have a satisfying “life cycle quality” or “life cycle performance.”

1.2.1 Life cycle performance of civil engineering products

There are many aspects to look at when evaluating the “life cycle performance” of a civil engineering product. Generally, the aspects can be divided into four groups. These are:
- political influence
- socio-cultural aspects
- economic effects
- technological impacts

The political influences are generated through changes in legislations or regulations. They may be national or international. Examples for political influences are changes in fire regulations, changes in standards or changes in demands for thermal conductivity. These changes may influence the life cycle performance of a civil engineering product. The product may not be able to meet new requirements and, therefore, needs to be replaced. For sandwich panels, this has happened over the last few years with regards to fire safety regulations.
Increased requirements have banned core materials that were popular a decade ago but do not meet today’s fire requirements.

Increases in tax laws may lead to higher maintenance costs for certain products. The same can be true when looking at the end of a product life cycle. Changes in regulations, regarding disposal and recycling, may induce costs that were unknown during the construction phase. For a sandwich panel structure, this may be a regulation to detach recyclable metallic faces from the core in demolition of a building.

The Socio-cultural changes are basically changes in customer demands. The taste of people changes over time. There are constant changes in working culture and living habits. Architectural changes in construction are the consequence. This, however, is not limited to the appearance of a building or structure but also effects functionality and even building materials. Changes in public perceptions towards a building material may change. Materials may get a bad ecological reputation and are, therefore, eliminated from the market. An example in the sandwich construction area is the use of mineral wool panels in Great Britain. In the early nineties mineral wool fibres were feared in Britain because of their carcinogenic potential. From a scientific point of view, it had been disproved that the common wools were emitting fibres with a potential health risk. Nevertheless, the public opinion was not changed by researched facts.

Economical effects are dominated by the fact that buildings generally require large investments. The investor, when investing into a structure, wants some benefit from his investment. He has earning expectations. These expectations can only be fulfilled if the building keeps its functionality over a certain time period. The time period estimated depends on the type of building. For an industrial building like a warehouse, for example, it may be relatively small but for a representative office building it may be very long. In order to keep the building functional, it is important that it can adapt to changes in utilisation. Such adaptability may, for example, have a great influence on its sale- or re-sale ability. Maintenance costs, which can also include costs for reconstruction after partial destruction that may, for example, occur after a fire, have considerable impact on the total costs of a building. The same is true for the end of lifecycle economy, the tear-down and disposal costs. Sandwich panels are generally employed because of their economical benefits. This is, however, particularly true for countries with high labour costs, where investments in expensive, but widely automated production plants are compensated through savings of on
site labour costs. In case of necessary refurbishment, for example after a fire, modular building kits generally offer a positive economical effect, as replacement is quick and relatively cheap.

Constant innovation in technology affects civil engineering products. Progressing methods of recycling, for example, may lead to a scenario, where a building material that was anticipated to be problematic at the end of its lifecycle, becomes uncritical or maybe even valuable as a new raw material.

New technologies often require new production environments. Nowadays, large production plants are less needed and often converted into office buildings or accommodate small high-tech production lines where very clean environments are required.

Progresses of investigation technologies into building materials may lead to the discovery that building materials, that were previously seen as unproblematic, turn out to be carcinogenic or toxic. The problems we have today with asbestos, which in the past was very popular, are a good example.

The most important technological influence for a civil engineering product is the guarantee of safe use over time. Building materials need to be designed in a way, guaranteeing adequate structural performance. If a structural building material cannot resist against the load impacts it receives, the building is damaged or may even collapse. In a worst case scenario, this may lead to loss of both, life and property. Therefore, the main task in regulation is to ensure adequate structural performance of building materials throughout the whole life cycle of the structure. Legally binding design procedures, which are very much harmonized across Europe, are the base to guarantee safe structural performance. For sandwich structures, such procedures are either defined in national approvals or will be defined in the new European standard on sandwich panels in the future.
1.2.2 Durability of sandwich panels in prEN 14 509

The new European standard on sandwich panels, prEN 14 509, makes a statement concerning durability. In this standard the statements can be found in chapter 5.2.3, “Durability and other long term effects.” Detailed information on testing scenarios is written down in annex B, “Durability testing method for sandwich panels.” The annex B has a normative character and is therefore
a legally binding document. In annex Z the standard gives an example of a CE marking, as it will be used in the future on sandwich panel packaging (see fig. 1-3).

The label gives information on all important mechanical characteristics of the product. It contains information on fire performance, permeability and insulation. But in the very last line, it also gives information about the outcome of durability testing. Different from most other items on the CE label, the durability line does not give a value. Durability for sandwich panels at the moment is a pass/fail criterion based on test results. It is also not possible to omit the information on durability by rating it NPD as it is possible with, for example, fire resistance or sound absorption. This means that the code at the moment takes a qualitative approach, assuming that a certain loss in strength is acceptable without further consideration in the design process. Such an approach is rather general and must be either uneconomic, when the strength of the materials in use is not exploited completely, or unsafe if the boundaries allowed for deterioration are too liberal.

For producers of sandwich panels the CE labelling will be of vital importance on a very competitive European market. Manufacturers will be able to cope with lower mechanical resistance values, meaning shorter allowable spans for their product, but failing in durability will lead to deprivation of the CE label, which means a significant competitive disadvantage. Having a whole chapter on durability in the standard plus stating the outcome of durability testing directly on the CE label, indicates the great importance durability has for a civil engineering product such as a sandwich panel.
1.3 Aim of project

Although a considerable amount of research has been performed in the field of sandwich panel durability, no comprehensive solution has been found to determine long term panel performance.

![Graph showing possible degradation patterns for tensile strength.](image)

So far, durability performance has only been evaluated qualitatively. This means that the loss in cross panel tensile strength under an artificial, durability-accelerating climate must stay within certain boundaries over time. The cross panel tensile strength is seen as an indicator for overall panel performance. Depending on the type of degradation pattern (see fig. 1-4), a core material is either fit for application or not. The boundaries chosen for acceptable loss of strength are lacking scientific foundation. Even a loss of 60% of the initial tensile strength can be acceptable in accordance with the new standard. In particular, such loss in strength is allowed without any impact on other relevant design parameters. This research tries to expound a more quantitative approach. Artificial ageing scenarios with relation to in-life performance of panels are introduced. Such scenarios allow a choice of planned service time. Instead of giving just boundaries, the outcome of durability tests on all material properties is considered and implemented in a durability related design procedure.

As a background for such durability testing, it is necessary to establish an accelerated ageing scenario, which can be performed in laboratory conditions. Such artificial climates need to be related to in-life conditions of sandwich panels. It is necessary to determine natural factors affecting a structure. Such factors, in particular temperature and humidity, are observed in an outdoor testing rig where different sandwich panels are constantly monitored. Together with a literature review on possible chemical degradation, reactions artificial ageing scenarios are developed. At the same time, mechanical properties after natural ageing are determined.
testing regime includes destructive tests on collected panels, which are at the end of their lifetime, coming, for example, from torn down buildings and non-destructive testing, performed regularly in the outdoor testing rig. Artificial ageing tests with a variety of climates are then performed on small scale samples, evaluating the tensile strength and stiffness of the structure over time. For the most important climates, such testing is enlarged by a complete small scale test regime, including compression and shear tests. The obtained results can be compared to the observations from the naturally aged samples.

As it is not possible to determine the important wrinkling strength after artificial ageing with the tests on hand, a new small scale test, fitting into a climate chamber for determination of wrinkling strength, is developed. At the same time, a mathematical model is established, which allows predicting the influence of changes in design parameters as observed in small scale testing after artificial ageing on wrinkling strength. The model is verified through comparison with results of the new small scale wrinkling test.

In a final step, design consequences including durability-related deterioration of mechanical properties are introduced.

The interaction of the different research items is also illustrated in the following figure (see fig. 1-5).

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**Research Procedure**

![Research Procedure Diagram]

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**fig. 1-5** overview of the research procedure, leading to determination durability implemented design values after a defined time and the condition of service.
1.4 Layout of thesis

Chapter one attempts to give a general introduction to sandwich panels as used in modern construction industry. It discusses the importance of durability evaluation of civil engineering products.

Chapter two provides an overview of the state of the art in sandwich panel technology. It gives general information on implemented materials, applications and the regulatory background. The emphasis, however, is on the mechanical analysis of sandwich constructions. Possible failure modes are described in detail.

Chapter three is concerned with the durability background of constructions and buildings. In particular, the impact of durability on design procedures and the necessity of predicting changes in mechanical behaviour is outlined. Then the chapter focuses on durability aspects for sandwich panel construction by introducing important factors, which can cause degradation in a sandwich structure and by presenting how the problem is currently dealt with in the sandwich standard and what the shortcoming of the current method is. Based on this background information, the necessary testing for this research can be chosen.

Chapter four describes the testing methodology applied to this research. Samples were tested after both, accelerated and natural ageing. The information gathered in an outdoor testing rig is presented. Furthermore, a new small scale test determining wrinkling strength is introduced. Test results are presented either in this chapter or, comprehensively, in Appendix 1.

Chapter five presents in depth the ageing and durability related chemical reactions that can lead to deterioration of mechanical properties. The chapter explains why different panel core materials require different ageing scenarios and discusses the development of surface temperature and internal humidity based on the previously described tests results. Ageing scenarios based on the chemical background of the material are proposed for the most important core materials.

Chapter six reviews the impact of deterioration in mechanical properties on design procedures and establishes a model incorporating losses in mechanical strength. In particular, the influence of a loss in cross panel tensile strength on the wrinkling strength of a panel is
implemented in the presented model. The proposed model is backed with information presented in chapter four.

Chapter seven contains conclusions and final remarks.
2 Sandwich panel construction; principles, background and literature survey

Over the last decades the commercial importance of sandwich panels in construction has been increasing tremendously. Developed in the early fifties, initially for cold stores and freezers, sandwich panels are used, today, in a variety of different applications different building types. In many respects they have displaced conventional cassette and corrugated sheet assemblies. Modern sandwich panel constructions offer excellent insulation properties in combination with advanced jointing techniques and fast installation. As a rule of thumb, the erection speed for wall panels is estimated at 6 m²/h and 7.5 m²/h for roof elements. The triumphal procession of sandwich panels is strongly connected to the increasing energy costs and the subsequently tightened heat conservation regulations. Though having gained a reasonable market share, sandwich panel construction remains poorly represented in technical literature and standard textbooks. Sandwich theory is not a subject taught in universities, not even in specialized universities, such as the University of Applied Sciences in Mainz or the Technical University in Darmstadt. Consequently, the building method is still often seen as a new method among architects and engineers although considerable experience has been gathered over the last fifty years.

2.1 General information

Surveys among panel producers and architects have shown that the majority of sandwich panels are used for external wall and façade applications (56 %), followed by roof applications (30 %) and usage for internal partition walls and ceilings (14 %). Sandwich panels are in most cases screwed to a supporting sub-structure. Very often such sub-structures are steel-made but reinforced concrete and timber constructions are also possible.

The biggest markets for sandwich panels in Europe are Italy, Spain, Great Britain, followed by Germany, Austria and Switzerland. Smaller quantities are produced in Turkey, Greece, the Benelux States and Eastern Europe, as well as in Scandinavia. The total volume of produced and assembled panels in the whole of Europe was estimated at about 51 million square meters in 1998. The number is still increasing and is estimated to reach 75 million square meters in 2005.
Development of sandwich panel production in Germany

![Graph showing the development of produced square meters of sandwich panels in Germany](image)

**Fig. 2-1 Development of produced square meters of sandwich panels in Germany (source of figures: Koschade (2002), numbers for 2005 estimated after consultation of major producers)**

Generally, sandwich panels are produced so that, after the elements are connected, a system width of 1000 mm is achieved. As modern panels are produced in a continuous production process, the element length is limited through transportation and lifting possibilities. Lengths of 20 meters and more are common. This is particularly true for roof elements as transverse jointing of panels is always problematic for such application. In lengthwise direction the junction between wall elements is achieved through tongue-and-groove joints. Overlapping techniques for the profiled external face are applied for roof panels. For special applications, such as climate rooms and cold stores, air- and vapour-tight jointing systems are available. In wall applications the joint is, in many cases, also used for the fasteners necessary to connect the sandwich structure to the supporting frame. Such fasteners are generally stainless or tempered steel screws and can be used in a concealed or open and visible manner. At the top and bottom end the cut edges of the panel are exposed to the environment, covered only with shades for protection from direct sunlight. Some joint geometries are implementing double tongues and sealing strips to improve air tightness. This is, however, not the standard case. Panel joints are relatively tight when considering air flow from inside the building to the outside. For air leakage at the usual service ability limit state, 10% of the value measured at 50 Pa pressure difference in the laboratory can be assumed. A typical 50 Pa value would be 2 m³/m²/h thus meaning 0.2 m³ per square meter panel area per hour air flow through joints. Moreover, the joint itself is streamed with small quantities of fresh air from the cut edges constantly. With regards to durability aspects, it has to be remembered that the panel core,
though in most areas protected from environmental influences, remains unprotected from air flow in the joint, at the cut ends of the panel, and in the corners of a building. It is here where the environment attacks the sandwich structure and causes ageing related degradation.

![Diagram of Sandwich Wall Panel, Supporting Elbow, Screw with Sealing, L-Profile, Drip Flashing, Sandwich Wall Panel, Supporting Elbow, Screw with Sealing, L-Profile, Drip Flashing, Internal Flashing, Rivet, External Flashing, Sandwich Wall Panel.]

*fig. 2-2 typical detail for footing (left) and corner (right) in sandwich panel construction (taken from Romakowski 2005)*

Double belt continuous lamination plants have made the production of sandwich panels fast and economically beneficial. The production process starts with the de-coiling and profiling of the metal faces. Then the core material is inserted between the shaped faces. When employing a polyurethane core, the liquid reaction mixture is sprayed evenly onto the lower face while the upper face is brought into position. The chemical reaction of the polyurethane forms a rigid auto-adhesive core material when moving along the double belt machine. The double belt keeps the two faces at a defined distance and determines the thickness of the ready panel. Mineral wool core panels employ either cut lamella techniques, where the wool is cut and turned, or mineral wool blocks with vertically oriented fibres. Glue is then sprayed to either the core or the faces before the panel is transferred to the double band. The ready sandwich panel leaves the double belt in a continuous flow at a speed of eight meters per minute or more. Saws then cut the panel to the desired length. At that stage, the panels are still warm and the core or the core face connection, in case of mineral wool panels, has not reached the full strength yet. To prevent damage the panels are cooled in a racking system. After reaching ambient temperature the panel is prepared for transportation. Panels are bundled to manageable stacks and protected through wrapping and boxing. Modern production lines are equipped with centralized control units, which allow changes in panel thickness at the push of a button. Changes in face geometry require more work as the complete rolling machine cassette needs to be swapped.
2.2 Sandwich panel materials

When looking at materials typically used in a sandwich panel, a large variety of sometimes very different components can be found. The fundamental principle, however, stays the same. A lightweight core with sufficient stiffness in a direction perpendicular to the faces separates two thin but high strength faces. Common core materials fulfilling these requirements are:

- Rigid foams
  - Polyurethane and polyisocyanurate (PUR / PIR)
  - Polystyrene (EPS / XPS)
  - Phenolic foams (PF)
- Inorganic fibres
  - Stone wool (MW)
  - Glass wool (MWG)
- Other core materials
  - Honeycomb cores (e.g. made from paper or aluminium)

Different core materials exhibit different properties. These properties do not only affect the mechanical strength of a sandwich panel but are also decisive when looking at the long term durability of a structure. Table 2-1 (Berner, 2002) offers an overview of the mechanical properties for core materials that are often used in sandwich panels.
<table>
<thead>
<tr>
<th>Property</th>
<th>PUR/PIR</th>
<th>EPS</th>
<th>XPS</th>
<th>PF²</th>
<th>MW</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal conductivity ( \lambda _{R} )  ((W/m \cdot K))</td>
<td>0.022-0.032</td>
<td>0.035-0.040</td>
<td>0.025-0.028</td>
<td>-</td>
<td>0.033-0.044</td>
</tr>
<tr>
<td>Shear strength ((N/mm^2))</td>
<td>0.08-0.15</td>
<td>0.09-0.16</td>
<td>0.18-0.5</td>
<td>0.05-0.15</td>
<td>0.03-0.2</td>
</tr>
<tr>
<td>Shear modulus ((N/mm^2))</td>
<td>1.2-5.0</td>
<td>3.0-7.2</td>
<td>3.2-8.4</td>
<td>2.0-4.0</td>
<td>2.0-15.0</td>
</tr>
<tr>
<td>Tensile strength ((N/mm^2))</td>
<td>0.07-0.22</td>
<td>0.08-0.17</td>
<td>0.34-0.52</td>
<td>0.03-0.1</td>
<td>0.03-0.6</td>
</tr>
<tr>
<td>Tensile modulus ((N/mm^2))</td>
<td>1.0-10.0</td>
<td>1.0-10.0</td>
<td>45.0-70.0</td>
<td>1.0-3.0</td>
<td>5.0-40.0</td>
</tr>
<tr>
<td>Compression strength ((N/mm^2))</td>
<td>0.10-0.16</td>
<td>0.10-0.18</td>
<td>0.20-0.70</td>
<td>0.08-0.2</td>
<td>0.10-0.15</td>
</tr>
<tr>
<td>Compression modulus ((N/mm^2))</td>
<td>2.6-6.0</td>
<td>1.3-3.5</td>
<td>15.0-20.0</td>
<td>2.0-8.0</td>
<td>6.0-15.0</td>
</tr>
<tr>
<td>Fire performance</td>
<td>mediocre</td>
<td>poor</td>
<td>poor</td>
<td>good</td>
<td>excellent</td>
</tr>
<tr>
<td>Density ((kg/m^3))</td>
<td>36-50</td>
<td>10-25</td>
<td>30-50</td>
<td>35-55</td>
<td>70-150</td>
</tr>
<tr>
<td>Durability (perceived)</td>
<td>good</td>
<td>excellent</td>
<td>excellent</td>
<td>unknown</td>
<td>mediocre</td>
</tr>
</tbody>
</table>

Polyurethane (PUR) or mixtures between polyurethane and polyisocyanurate (PIR) are the most common among these core materials. They represent about 75% of the total market. Mineral wool core panels own the second largest market share at about 20%. The rest is divided between the other core materials. The main reason for the extensive use of polyurethane sandwich panels is the combination of excellent material properties and good processability at a reasonable price. Though sandwich panel prices are subject to constant change due to fluctuating raw material costs, PUR panels sell at a price between 25 and 30 Euros per square meter while mineral wool core panels sell at roughly 30 to 35 Euros per square meter. The main reason to employ mineral wool core panels is simply the excellent fire performance. While mineral wool panels can reach an A2 classification according to EN ISO 1182 and EN ISO 1716 and easily reach ninety minutes or more of fire resistance, PUR panels need to be equipped with fire retardant to reach a B classification. Thus, these panels cannot be used for many fire sensitive applications. The desire to combine good fire performance with the good process ability of rigid foam has inspired research on phenolic resin foams. Phenolic resins are thermosetting in opposition to thermoplastic polyurethane thus providing greater stability when attacked by fire and high temperatures.

² Results based on research carried out at FH Mainz
Depending on how a sandwich panel is used, what impacts it has to withstand and what excitations it is exposed to, the panel can be designed choosing from an almost never ending variety of face materials. For construction applications the most common materials are:

- metallic facing
  - steel sheet
  - aluminium sheet
  - copper sheet
  - high-grade steel sheet
- wooden facing
  - chip board
  - Oriented Strand Board (OSB)
  - Gypsum boards
- plastic facing
  - glass-fibre reinforced plastic (GRP)
  - epoxy-glass resin

Among these, steel sheet is by far the most common facing material. Over 90% of the sandwich panels currently sold in the construction sector is equipped with steel sheet as a facing membrane.

Today modern sheet steel is equipped with a large variety of different coatings (Davies, 2001). Figure 2-3 indicates the different layers. Each layer has a special function. The outer colouring can be a liquid film or powdered coating system. A large range of organic materials and a wide spectrum of colours are available. The surface is generally protected from damage during storage, transportation and installation through a tear off protective foil. Such foils must be removed directly after installation because peeling-off after exposure to solar radiation becomes problematic. For oxidation protection of the steel sheet itself, corrosion protection through hot dip refining is employed. Hot dip galvanizing and hot dip aluminizing provide homogenous all-over protection of the panel. This is particularly important for the shoulders of bends occurring in the profiling of the face. Together with the organic coating external sandwich panel faces fulfil corrosion protection class three according to DIN 55928 while inner faces reach class two. With regards to durability aspects, sandwich panel faces are
well protected from environmental impacts. Latest research has shown that also the face side connected to the panel core provides excellent corrosion protection (Aalto, 2004).

Here, the coating includes an epoxy or polyester based back-face coating, functioning as bonding agent. Recapitulating, it can be said that a metal faced sandwich panel does not only consist of the three layers “face – core –face” but each face consists of up to nine different layers itself. As stated earlier, adequate bonding between core and face is of vital importance to the structural behaviour of a sandwich structure. This does, therefore, not only mean adequate bonding between face and core but also adequate bonding between the different face-layers themselves.

Almost as variable as the surface colour is the surface geometry. It ranges from ribbed or bead profile to trapezoidal shapes with corrugated wave patterns and micro-line profiles in-between. Although difficult to produce, as even small unevenness attracts attention in the ready building, totally flat sandwich panels are available.

In order to fix the sandwich panel to the supporting structure self-drilling screws are applied. A variety of approved screws are available to the market. They vary considerably in length depending on the thickness of the panel that needs to be mounted. Typical screw diameters are between 5 and 8 mm. Most screws are equipped with a sealing washer. The washer protects the drilled hole from moisture penetration. This is, however, not necessary for concealed fixings. To spread the load introduced through the fastener onto the panel, additional load spreading bases can be used. Typically, sandwich structures are fixed to the supporting sub-structure at every support. Depending on the static requirements, between two
and four screws can be used at each support. Higher numbers are required at building corners where wind suction reaches peak stresses. When looking at durability aspects of the fixing there are two possible items of consideration. On the one hand the screw itself may show durability effects. With regards to this it can be noted that the screws themselves are protected from corrosion even in harsh environments. Sometimes even stainless steel screws are used. On the other hand the screw, when penetrating the panel faces, destroys the sealing of the core from the external atmosphere to some extend. The damage on the panel caused by the penetrating screw is relatively small. For example four 5.5 mm screws on a panel with an allowable system length of five meters damage not more than $6 \text{ mm}^2$ per square meter (0.006%). At the same time, the damaged area is sealed by the washer.

### 2.3 Application of sandwich panels

There is a wide field of application for sandwich panels in the construction business. They are used in industrial buildings like shops and warehouses, in business building construction, as well as for domestic and office buildings. Sandwich panels are also suitable for refurbishment and modernisation of existing construction. Trade fair and exhibition buildings are also very likely to consist of sandwich panels at least in some parts. Special applications are, for example, the use in cold stores, taking advantage of the excellent thermal insulation properties of the panel’s core.

The biggest market share for sandwich panels is in industrial buildings. It is here that the benefits of sandwich construction can be taken advantage of. Panels are prefabricated in the factory. They are delivered onto site in the accurate shape they are needed. The panels can be mounted directly to the supporting structure that can vary from steel frame, which is the most common, to wood or reinforced concrete.

Erection is very fast and can usually be done within a few days. Sandwich panels are lightweight and, therefore, minimize the amount of extra dead load that is added to the building. Architects are inspired to use sandwich panels in both, low priced shops and warehouses, as well as ambitiously styled facades.
2.4 Regulatory background

The use of sandwich panels is currently regulated in numerous different binding documents for each country in the European Union. Nevertheless, all documents are largely based on a joint ECCS\textsuperscript{3} - CIB\textsuperscript{4} recommendation.

2.4.1 ECCS-CIB Recommendation for Sandwich Panels

For a long time the only European regulation for sandwich panels was a joint ECCS and CIB recommendation (ECCS, 2000). The document was prepared by ECCS TWG\textsuperscript{5} 7.9 and CIB W56. The final draft was issued in 1999. Until now this paper is one of the most important sources for engineers dealing with sandwich panel design. It gives advice on almost all important aspects of sandwich construction. Requirements on safety and design procedures are explained. Mathematical ways of calculating the effects of different actions are given. The evaluation of resistances is described. Design procedures and quality control methods are discussed. Detailed description of testing procedures for both, quality control and determination of material property values for calculation are given.

The recommendation, however, is not a binding document. Its legal base is strictly informative. Most European countries, therefore, have their own regulatory documents for sandwich panel design and construction. Many of these are largely based on the ECCS-CIB recommendation. The biggest differences are in the definition of safety factors and dictation of external quality control. When looking at design procedures and testing, the biggest difference from the rest of Europe can be found in France where the predominant design

\textsuperscript{3} ECCS – European Convention for Constructional Steelwork

\textsuperscript{4} CIB – Communiqué International de Bâtiment

\textsuperscript{5} TWG – Technical Working Group
procedure used is design by testing, as in variation to design by calculation, which is recommended in the ECCS/CIB report.

With regards to durability, the recommendation proposes performance based methods. The methods in principle match the European Standard test procedures while proposing only two tests (DUR 2 and 3, see chapter 3.4.2). The test evaluation differs only slightly.

2.4.2 German approvals

Lacking a standard and not being listed in the Building Regulations register, sandwich panels need to undergo approval procedures in Germany as in most other countries. A technical approval from the German Institute for Building Technology (DIBt) comes with all necessary information for the design of a sandwich panel. The necessary proof of stability and fitness for purpose calculations are defined in appendix A of the approval document. The necessary information on the sandwich structure itself is listed in appendix B. This includes the required safety factors. The resistance values are determined through testing. The test procedures are generally in accordance with the test proposed in the ECCS-CIB recommendation. To check the correctness and compliance with the stated material properties, a regular internal examination of the most important values is required from the producers. The obtained results must be recorded and, upon request, submitted to the DIBt. Furthermore, biannual external examination from independent institutes is required. Only with this, the producer is allowed to affix the approval symbol, the so-called Ü-symbol, to his products.

The required proof for fitness of purpose can be based on either project specific individual requirements or type approval using allowable span tables.

With regards to durability, there are no requirements from the DIBt. To achieve a technical approval in Germany, no durability evaluation is undertaken. The time dependent loss in structural performance is simply not accounted for. This is also true for the proposed safety factors. They do not consider durability.

2.4.3 European standard prEN 14 509

As the ECCS/CIB recommendation is not a binding document and sandwich panels are sold over the whole of Europe, inquiries for a European standard became more frequent. In consequence CEN⁶/TC⁷/128/SC⁸/11 was formed to prepare a draft for an international standard.

---

⁶ CEN – Comité Européen de Normalisation
⁷ TC – Technical Committee
By and large, the standard was based on the already existing ECCS/CIB recommendation. The first draft of prEN 14 509, “Self-supporting double skin metal faced insulating sandwich panels – Factory made products – Specification,” was published in 2002 (prEN 14 509, 2004). The final voting process, however, ended with refusal in January 2004. The ratification, which was planned for summer 2005, will, therefore, be delayed by six months to one year. The document will then be binding after a transition phase in all European countries.

The work of CEN/TC128/SC11 is based on a mandate given to CEN by the European Committee. The mandate is based on the “Basic Documents” defined by the European Construction Products Directive (CPD 1988). These documents define essential demands that need to be tackled in the EN. The key issues are:

- mechanical stability
- fire safety
- health and environment
- safety in use
- noise protection
- energy economy

“Safety in use” in this list includes durability, the performance of a structure, or material over time. The mandate is further specified in a guidance paper (Guidance Paper F concerning CPD, 2004) prepared by the Standing Committee. Such guidance papers try to establish a common understanding between the European Commission and the member states. They are, however, legally non-binding documents. In point 1.1, which is the first sentence of the paper, durability is defined as “...the property of lasting for a given or long time without breaking or getting weaker.” For durability evaluation the ECCS-CIB recommendation was adopted in prEN 14 509. An additional test for foam core panels was added (DUR 1, see chapter 3.4.2).

Once the standard becomes a legal document, it will be possible for all manufacturers of sandwich panels to comply with it. In order to prove compliance, the products will carry a CE marking. The CE marking contains a statement of principle properties, giving all necessary figures for design that is carried out in all the different European states.

2.4.4 British agreement

For the British market approvals are issued by the British Board of Agrément (BBA 2004). They are, in principle, comparable to the German approvals. A technical specification of the
described panel type is followed by the information on important design data. Unlike in the German approval, permissible load tables are included in the British document. The tables are produced in accordance with the ECCS/CIB recommendation. Generally, it can be said that when comparing the two approvals, the German very much concentrates on structural performance and design while the British document provides restricted information in this area but tackles other important subjects such as installation, maintenance, and durability. The durability-related chapter is exclusively considered with corrosion impacts on the panel faces. Even a table on minimum service life under coastal and inland conditions is provided.

<table>
<thead>
<tr>
<th>Sheet material</th>
<th>Minimum service life (years)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Inland</td>
</tr>
<tr>
<td>Aluminium alloy</td>
<td>40</td>
</tr>
<tr>
<td>PVF-coated aluminium alloy</td>
<td>20</td>
</tr>
<tr>
<td>ARS-coated aluminium alloy</td>
<td>20</td>
</tr>
<tr>
<td>Colorcoat HP5200 steel</td>
<td>18 to 27</td>
</tr>
</tbody>
</table>

*Fig. 2-5* information on sandwich panel service life taken from BBA approval (BBA 2004)

This approach is again based on the assumption that the sandwich panel core material keeps its properties over life without changes.

Both, the German and British approval are based on a regular monitoring system. While monitoring intervals in Germany are twice a year, the British system dictates external production examination and check of test results on request of BBA.

### 2.5 Mechanical behaviour and literature survey

The mechanical behaviour of sandwich structures has been studied analytically in detail in the 1960's. Allen (1966) and Plantema (1966) established the sandwich theory. The background was not the application in the construction industry but rather the development of comprehensive mathematical modelling for aeronautic and maritime applications. Simplified design methods were then developed for the construction sector based on the elastic compound theory (Wölfel, 1987). With the increasing demand for a practical design method for sandwich structures in building applications, Berner (1997 and 1998) adapted this theory and introduced sandwich design procedures. These procedures are well accepted and were
incorporated into the ECCS recommendation (2000), as well as into the new European Standard (prEN 14 509) and any German approval (DIBt 2004).

The most important point in sandwich theory, which is a theory of elastic compound, is that the Bernoulli hypothesis of non-changing cross sections no longer applies. In sandwich theory deformations and associated stresses caused by shear deformation of the core need to be considered. The core also influences the over all performance of the panel by providing support for the faces under compressive stress, hindering them from early buckling, the so-called wrinkling failure. Unlike most conventional constructions, the temperature differences between inner and outer face may cause stresses exceeding those induced through wind or snow loads and, therefore, need special consideration in the design process.

**Rigid compound**

\[
\begin{align*}
\text{shear stiffness } & \quad G = \infty \\
\gamma_1 &= -w' \quad \delta = 0
\end{align*}
\]

**Elastic compound**

\[
\begin{align*}
\text{shear stiffness } & \quad 0 < G < \infty \\
\gamma_1 &= 0 \quad \delta = 0
\end{align*}
\]

fig. 2-6 comparison of rigid compound (Bernoulli hypothesis) and elastic compound illustrating the rotation of the different compound members.

Sandwich panels equipped with plastic core materials show increasing deflection under constant loading over time. The so-called creep effect is caused through shear stresses in the core. In design calculated deflections, employing a long term shear modulus for self-weight and snow, are superposed with deflections calculated on the base of a short term shear modulus for temperature and wind loads. Although accurate figures for the long term shear modulus are generally determined through testing for every panel configuration, typical long term shear moduli for snow load are one-third and for self-weight one-eighth of the initial value.

The design of sandwich structures is nowadays manageable by any designer and has found its way into designer's handbooks such as the "Schneider design charts for engineers and
architects" (Berner, 2002), which is a standard handbook for engineers and architects in Germany. For deeper information regarding mechanical behaviour and other important aspects of sandwich panels, Davies (2001) provides an excellent and comprehensive source. While steel-faced sandwich beam applications, which are subject of this work, are enjoying a wide range of applications, sandwich panels with a load-bearing behaviour parallel to their faces are currently becoming increasingly popular. In principle, such panels follow the same load-bearing behaviour. A simplified design method was presented by Berner and Pfeiffer (2002 and 2004).

All simplified design methods are based on a design against characteristic strength properties based on experimental results. The typical failure modes of a sandwich structure are presented in the following.

### 2.6 Failure Modes

Resulting from the above described load-bearing behaviour of a sandwich panel, a variety of different failure modes may occur when exceeding the maximum load-bearing capacity. All failure modes must be checked when designing a sandwich structure.

In the following, the failure modes valid for panels with thin metal faces, both profiled and flat, are described. The pictures illustrating the failure modes are taken from Koschade (2002).

#### 2.6.1 Face yielding

The introduction of a bending moment into a sandwich panel results in tension and compression of the face material. It may be that the tension or compression stress in the face exceeds the yield strength (see fig. 2-7 and fig. 2-8).

![fig. 2-7 panel face yielding at mid span](image)

![fig. 2-8 panel face yielding above intermediate support](image)

The stresses, occurring in the sandwich panel face, can be determined with the help of sandwich theory. The design is then carried out against the characteristic yield strength of the applied steel sheet.
2.6.2 Face wrinkling

The wrinkling of the face under compression is a typical and very important failure mode for sandwich panels with membrane-like faces (see fig. 2-11 wrinkling at mid-span and fig. 2-10 wrinkling at intermediate support). As stated before, in a loaded sandwich panel, one face is in tension while the other is in compression. A membrane under compression has, on its own, no stability. It fails immediately through buckling. For membranes in a sandwich panel, this is no longer true.

![Diagram](image)

**fig. 2-9** Illustration showing activation of bedding capabilities of the core. The face membrane causes compressive and tensile stresses in the core.

The panel's core provides a lateral support for the thin face and hinders it from an early buckling failure. The lateral support is activated when the face deforms in a wave-like pattern and induces stresses on the core material ($\sigma_c$). In particular, when looking at the tensile stresses of the core, it becomes obvious that a failure results in immediate wrinkling of the face. Wrinkling is one of the most critical failure modes in sandwich panel construction. For sandwich panel design, the wrinkling capacity of a panel very often determines the ultimate limit state.

![Images](image)

**fig. 2-11** wrinkling failure of compressed face in single span beam  
**fig. 2-10** wrinkling failure at intermediate support

Like many parameters, the wrinkling strength of a panel is determined through testing. A full scale bending test and a simulated central support test, which is also carried out at full scale, provide the necessary values.
2.6.3 Shear failure of the core

It has been said earlier, that for a sandwich panel with membrane like faces, the whole shear load is taken by the panel’s core. Wherever there are high point loads, as for example over supports, it is possible that the panel core fails through shear. For a single span panel this failure generally occurs close to the supports (fig. 2-12). Multi span panels are likely to fail in shear close to an intermediate support.

The shear strength of a sandwich panel is determined through small-scale testing on a short sandwich beam. The failure mode occurring in such test can be seen in figure 2-13.

2.6.4 Core crushing

Intense local loading may not only lead to shear failure but can also cause local crushing in the core. Especially in panels with membrane like faces, point loads are almost directly transferred to the core and may lead to a local compression failure in the core (fig. 2-14).

Small scale compression tests are the most simple methods to determine the allowably point loads for a sandwich structure. The obtained figures are, however, on the conservative side as the contribution of stresses through to face to surrounding core areas are not taken into consideration. More advanced tests are implemented in prEN 14 509 but little experience has been gathered so far.

For some work not driven so much by every day application such as research, deeper knowledge of mathematical sandwich analysis is useful. Linke (1978) described, in accordance with Plantema (1966), the interaction of core and face in the wrinkling behaviour
of a sandwich structure. As this mathematical prediction of wrinkling strength is not sufficiently accurate when comparing with experimental results, efforts were taken by Baehre (1988) and Pfeiffer (2000) to find an easy and cheap small scale test determining the wrinkling strength. However, both failed to establish a small scale test, which was able to substitute for large scale testing. The reason was the disregarding of pre-wrinkling deformations occurring in large scale reference tests. For the investigation of durability-related degradation in mechanical properties, it is desirable to have a small scale wrinkling test available. New efforts to establish such testing on samples, at a size manageable in climate cabinets, were undertaken in this research. The effect of the influence of face deformations prior to wrinkling failure was also discussed by Wolters (2002). Deformations of the sandwich face are a common effect in the production process. In order to take such deformation into account mathematically, it is important to gain knowledge about the shape of such pre-wrinkling deformation. A method for accurate surveying of such deformations was first conducted in this research and was presented in Schlüter, Pfeiffer et al. (2004), as well as in chapter 6.2.1 of this report.
3 Durability; background and literature survey

The determination of long term performance in civil engineering products is of increasing importance. Sarja (2002) gave a general introduction to the field and underlined its importance by giving examples and figures, which illustrate the economical impact. Because of this enormous economical impact, the CPD (1988) in Article 3 required the insurance of adequate structural behaviour “during an economically reasonable working life.”

General information on polyurethane was presented by Uhlig (2001). He describes products and applications, as well as basic chemistry related to isocyanates. However, the only information given on durability is that admixtures increasing the durability performance of PUR foams exist. No background information is given. The same sort of general information for polystyrene foams was given by van Dorp (1993 and 1996). With regards to durability, van Dorp argued that the issue is irrelevant for polystyrene foams as their chemical structure tends to melt before ageing effects can come into effect. The argument was backed up with information on polystyrene foam applications. Such applications, e.g. polystyrene foams in road foundations, were also presented by Duškov (1998).

Adequate methods for predicting the time-dependent changes in mechanical properties exist for many building materials and also for plastics. DIN ISO 2578, for example, uses the Arrhenius function in combination with test results obtained from material property testing to predict the long term mechanical performance of plastics. Similar methods have been used in connection with district heating pipelines as described by Hoffmann (2002) and as standardized in prEN 253. Such methods are, however, not adaptable to rigid plastic foams as these tend to melt at temperatures little above their service temperatures.

It is one approach of this research to investigate old sandwich panel products, which have been taken out of service. Similar approaches have been made by Götze (1988) who took samples from polyurethane foams used as roof insulation material in a conventional roof cross section. But he only concentrated on changes in compressive strength and thermal insulation, as these are important factors for the particular application. Similar results were described by Zehender (1986) who investigated gap filling glue (in literature also found as “foam fitting glue”). The durability impact on compressive strength has been studied in greater detail by Friedrichs (1998) who, after an initial drop, found an increasing compressive strength in
polyurethane foams over time. The report lacks background information on choice of ageing scenario and sample geometry.

A lot of research effort has been put into the prediction of loss in thermal insulation performance of rigid polyurethane foams. Such loss in thermal insulation can be caused by diffusion of blowing agents from the cell matrix and was described by Walter (1992 and 2000). Walter developed a model calculating the diffusion processes in a polyurethane sandwich panel core matrix. The model is based on theories for drying of porous materials as described by Newman (1931) and heat convection as described by Schack (1969). The report states that the loss of insulation ability in a sandwich panel application is minimal. The same results were described by Kohonen (1990) who used finite element analysis to get to the same result. Both methods require determination of diffusion coefficients for relevant gases in a polyurethane matrix. Relevant figures are, for example, given in Pompeo (1993).

Affolter described the general degradation possibilities in thermoplastic materials. In particular, oxygen is described as a necessary chemical reaction partner for deterioration processes in cellular foams. This research tries to combine the fact that oxygen is a necessary reaction partner for deterioration and looks at the time-dependent oxygen contents of cellular polyurethane matrixes based on the models described for deterioration of insulation properties.

When looking at mineral wool cores, the deterioration is dependent on the loss of binder strength in the fibre connections. The deterioration of urea-formaldehyde resins, which are predominantly used in mineral wool cores, have been described in Dunky (2002). In the report deterioration of resins was indirectly measured through detection of emitted formaldehyde.

Such deterioration largely depends on climatic impacts on sandwich structures. Temperature impacts can be calculated as described by Bark (1992). In this report the calculation method is verified against results obtained from in situ temperature testing. Humidity impacts, which are particularly important for mineral wool core panels, need to be determined through moisture testing inside the sandwich structure. This can be done only insufficiently correct through regular (once a month) weight measurements as described by Tiainen (1991). Constant monitoring is required and was performed in this research.

Jungbluth (1986) in his comprehensive report on sandwich panel analysis was already aware that the properties of polyurethane foams are not only temperature but also time-dependent. Unfortunately, Just (1995), who investigated a small number of foam core materials under different temperatures, found that this time dependency follows a pattern in cross panel tensile
strength, which is mathematically difficult to describe. Nevertheless, the panel tensile strength perpendicular to the faces after artificial ageing was seen as a good parameter for evaluation as it includes and tests all layers of a sandwich panel cross section. This test pattern was, therefore, also adopted by Berner et al. (1994) who investigated the decrease of bond strength between core and face for different face materials in combination with mineral wool. A variety of climates, including climate cycles, was conducted. The outcome was that some material combinations exhibit dramatic changes in properties. The report takes a rather quality-driven approach and distinguishes materials suitable for sandwich panel application from unsuitable materials. Limit values separating these two are, however, lacking. It was only in the preparation of prEN 14 509 that such limit values were required. As the producers of the standard felt unhappy with values lacking a scientific base, a comprehensive research, trying to gain more information on durability aspects in sandwich panel core materials, (ASPAN research) was initiated. The ASPAN consortium investigated a large variety of core materials under a multitude of climates varying in both, humidity and temperature (ASPAN, 2004). An ageing model for mineral wool core panels based on test results could be established (Reentila, 2003). During the research it became clear that the cross panel tensile strength is only one important parameter. Other parameters such as shear and wrinkling strength, which are even more important for sandwich panel design, also need to be taken into consideration. This means a change from a quality driven approach to a quantity-based evaluation of test results. This report tries to contribute to such an approach.

In practice, the terms “durability” and “ageing” are often used in the same sense. There is, however, a clear definition for the two terms in literature. For the purpose of this work, the two terms are defined in the following.

### 3.1 Definition of ageing

Statistics on service life for civil engineering products indicate that in 50% of all cases ageing is the reason for putting a construction out of action. In the remaining 50% it is the inability to withstand environmentally induced loads (Sarja, 2002).

Ageing in this context means that a building is not able to fulfil increasing demands. These demands may be of technological, functional, economical, or ecological nature.
An example for technological ageing is the conversion of domestic buildings into office space. In many cases the old structure is not able to fulfil the increased demands towards load-bearing capacity concerning life loads.

In many aspects ageing and durability interlink. Economical ageing, for example, is often a result of increasing maintenance and operating costs. This effect is frequently connected with deficits in durability.

When looking at individual test samples, ageing is often used with a different meaning. Accelerated ageing, for example, means that the environment around a sample is controlled in a way, leading to a rapid run through the life cycle of the specimen.

### 3.2 Definition of durability

Durability is the ability of a construction to withstand environmentally induced excitations. These excitations may be even more crucial than static or dynamic loading. In general, one can distinguish between physical loading induced by weather (i.e. temperature, humidity and radiation), chemical loading (i.e. salts like chlorine, carbon dioxide, sulphuric compound, etc), and biological loading (i.e. insects, fungi and plants). For the purpose of this research, durability is defined as the ability of a sandwich panel to withstand weathering impacts, particularly temperature, which may also be induced by solar radiation on the surface of the panel, and humidity. Durability, most likely, includes a degradation in mechanical properties.

### 3.3 Durability impact on design procedures

Design procedures used for every day engineering usually incorporate durability related changes in mechanical properties in safety factors. This may be through rather global safety factors or specific factors just for ageing-related decline.

#### 3.3.1 Statistical background of design procedure

Any engineering design is based on a very simple equation:

\[ S_d \leq R_d \]
The equation shows that the design load action is smaller or equal to the design resistance capacity. But, when looking at the characteristic values for load and resistance, the equation is as follows:

\[
\gamma_q \cdot S_c \leq \frac{R_c}{\gamma_M}
\]

In the design of sandwich panel construction, the resistance values derive from testing. The most important factors for the calculation process are the shear strength and modulus of the sandwich panel core, tension and compression capacities and moduli of the core and, finally, the wrinkling capacity. With these basic values, a design against all failure modes as described in 2.6 is possible. When determining the mechanical properties through testing, it is imperative to do a population of tests. The outcome will generally be a Gauss normal scatter (see fig. 3-1). The 5% fractal of this population generally forms the characteristic value.

![Gauss normal scatter](image)

**fig. 3-1 Gauss normal scatter of load action (S) and resistance capacity (R)**

The same normal scatter applies to the load action. The possibility of failure, where the action load is bigger than the material resistance, can then be written as a function of resistance and load action:

\[
P_f = P\{R \leq S\}
\]
By changing the safety factors in equation 3.3-2, it is then possible to fulfil the requirements given in EC\textsuperscript{10} part 1, asking for a safety level (or possibility of failure) of $10^{-3}$ for serviceability and $10^{-6}$ for structural failure when equation 3.3-1 is fulfilled.

### 3.3.2 Statistical changes over time

Over time the situation illustrated in figure 3-1 changes. From a statistical point of view, the impact on a structure over time usually decreases as the expected remaining life span is becoming shorter. For example, the most severe flooding in a 100 year period is possibly delivering more water than the worst flooding in a 10 year period; the strongest storm within 100 years is considered to have higher wind speeds than the strongest storm within a 10 year period.

![Change of normal scatter over time](image)

**Fig. 3-2** changes of Gauss normal scatter for load action and resistance capacity over time. Lines indicate change of mean value.

At the same time the resistance decreases due to ageing. Therefore, equation 3.3-3 can be changed to

\[
\text{eq. 3.3-4} \quad \mathbb{P}_\tau(t) = \mathbb{P}\{R(t) \leq S(t)\}
\]
The possibility of failure over time is a function of resistance over time and load action over time.

The designer has little or no influence on $S(t)$ but great influence on $R(t)$ by choosing adequate materials. Therefore, products need to be designed in a way ensuring that they will still meet safety expectations after a certain time period. Depending on the structure, this period may be something between 30 years for a simple commercial structure to something like a 100 years for a unique highly reputable building.

3.4 Evaluation of long term performance for sandwich panels

The evaluation of long-term performance is generally based on the knowledge that certain introduced excitation scenarios, the structure has to undergo during its lifetime, lead to ageing of the structure. Artificial ageing scenarios are derived from this fact.

3.4.1 Factors causing degradation

When concentrating on the mechanical performance of sandwich panels, the factors causing degradation are:

- long-term loading (self-weight and snow)
- movement and forces caused by temperature differences between the inner and the outer sides of the panel
- repeated loading (wind, foot traffic)
- internal moisture (moisture inside the panel)
- high temperatures (caused by solar radiation on the outer face)

At the moment it is not possible to investigate the long-term effects for sandwich panels by calculation. Therefore, the durability effect is generally determined by exposing samples to a condition where ageing factors, such as temperature, humidity, or repeated loading are exaggerated, in a way leading to premature ageing. The specimen is then brought back to laboratory conditions and testing is performed. For plastics -- and PUR, PIR or EPS are plastic foams -- this procedure is standardised in, e.g., DIN ISO 2578, "Plastics - Determination of time-temperature limits after prolonged exposure to heat.” This standard is a very general approach to the ageing of plastics through exposure to heat. For some core
materials, such as mineral wools, temperature is believed to play a less important part towards ageing. At this point, it is the combination of moisture content and temperature inside the panel that determines the ageing rate (Reentilä, 2003).

### 3.4.2 Durability testing in prEN 14 509

In order to evaluate the durability of sandwich panels, prEN 14 509 contains three different ageing tests, simulating ageing through moisture and temperature. The tests are called DUR1, DUR 2 and DUR 3. For all durability tests, DUR1 to DUR3, it is agreed, that the tension capacity of a 100mm x 100mm sample is an indication for the mechanical behaviour of the full panel. For mineral wool specimens, the dimensions can be extended to 150 or 200mm edge length, taking the inhomogeneity of mineral wool cores into account. A set of specimen is tested under laboratory conditions (23°C, 50% RH\(^{11}\)) first. The mean value of the determined tension capacity is taken as \(R_0\), the resistance after no cycle. Accelerated ageing in a climate chamber is then performed. The exposure environment changes, depending on the kind of core material tested and the planned external colour. For plastic foams, temperatures of up to 90°C and low humidity climates are dictated. Organic wool cores and EPS-cores are exposed to climates of 65°C and a relative humidity of 100%. For core materials that are new to the market, both, exposures to high humidity and high temperatures, as well as to temperatures below freezing were required until the latest version of the standard. Latest research results (Davies, 2004) have shown that some of the established core materials were not able to fulfil the proposed DUR 3 cycle and, therefore, would, if they were newly introduced, not be considered fit for purpose. To maintain fairness in competing core materials, the test was eliminated from the latest code document.

It is the intention of all testing in prEN 14509 to control the shape and pitch of the strength loss over time curve for the core material. Possible examples of strength loss curves were presented in figure 1-3. Figure 3-3 shows how a core material with an accelerating deterioration pattern is identified. Any curve that crosses the hatched area fails the test. When looking at the remaining strength after the artificial ageing process, substantial loss rates are accepted. Only if the tension capacity drops below 40% of the initial strength, the material has failed to pass the test.

\(^{11}\) RH - Relative Humidity
fig. 3-3 strength loss over time curves for a core material with decelerating decay speed (left) and accelerating decay speed (right). The hatched area indicates the required minimum performance as defined in DUR 2

3.4.2.1 DUR 1 testing

The DUR 1 tests concentrates on the influence of temperature on ageing. It is, therefore, designed to test rigid plastic foams such as PUR, PIR (whether the foam is auto adhesive or not) and PF. The test climate is:

<table>
<thead>
<tr>
<th>Table 3-1 Excitation in DUR 1 testing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature</td>
</tr>
<tr>
<td>90 °C(^\text{12})</td>
</tr>
</tbody>
</table>

One set of specimen is tested after each period and the mean values are recorded. The lowest mean value found in the course of testing is recorded as \(R_{\text{DUR1}}\); the result after 24 weeks is recorded as \(R_{24}\). The test is passed when:

- \(R_{\text{DUR1}} \geq 0.5 \, R_0\)
- the 5\% fractal of \(R_{24} \geq 0.04\) MPa
- dimension changes in thickness is less than 5\%

\(^{12}\) depending on colour group the test temperature may be reduced to 75°C (light colours) or 65°C (very light colours)
3.4.2.2 DUR 2 testing

The DUR 2 test is designed for core materials, such as mineral wool and XPS that are vapour open and, therefore, sensitive to humidity. The idea of the test is to keep the specimen at a constantly high temperature and humidity. The panels are, therefore, kept in a closed container over water that is heated to approximately 70°C, the so-called tropic box. This leads to an environment of:

<table>
<thead>
<tr>
<th>Temperature</th>
<th>Humidity</th>
<th>Exposure Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>65 °C</td>
<td>100 % RH</td>
<td>7, 28, (56) days</td>
</tr>
</tbody>
</table>

The standard says that a set of samples must be tested after 7 days (R7) and after 28 days (R28). Occasionally, further testing after 56 days, giving R56, becomes necessary. This depends on the outcome after 28 days. The test is passed when:

- \( R_{28} > 0.4 \, R_0 \)
- \( R_7 - R_{28} \leq 3 \, (R_0 - R_7) \)
- or, if the 2nd condition is not fulfilled: \( R_{28} - R_{56} \leq (R_7 - R_{28}) \) or \( R_{56} \geq 0.4 \, R_0 \)

3.4.2.3 DUR 3 testing

The DUR 3 cycle is relevant for core materials that are new to the market. These materials have to undergo all three tests, DUR1 to DUR3. The test is typically performed in a climate chamber with controllable temperature and humidity. The DUR3 test cycle requires the specimen to undergo the following procedure:

<table>
<thead>
<tr>
<th>Temperature</th>
<th>Humidity</th>
<th>Exposure Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>70 °C</td>
<td>90 % RH</td>
<td>5 days</td>
</tr>
<tr>
<td>-20 °C</td>
<td>-</td>
<td>1 day</td>
</tr>
<tr>
<td>90 °C</td>
<td>&gt; 15 % RH</td>
<td>1 day</td>
</tr>
</tbody>
</table>

One sequence of these three climate conditions forms one test cycle. A single test cycle, therefore, takes one week. The standard requires testing a set of samples after one single cycle.
(R₁), after five cycles (R₅) and, if necessary, after ten cycles (R₁₀). The whole testing time may amount up to 10 weeks. The test is passed when:

- R₅ > 0.4 R₀
- R₁ - R₅ ≤ 4 (R₀ - R₁)
- or, if the 2nd condition is not fulfilled: R₅ - R₁₀ ≤ R₁ - R₅ or R₁₀ ≥ 0.6 R₀

The DUR 3 testing regime was eliminated from the latest draft of prEN 14509 in spring 2004. The reason for this was that some of the currently operating sandwich panel cores would not pass the test and it would be unlawful to set higher demands for new materials than for materials that are currently in the market.

3.4.2.4 Wedge test

In addition to the previously described tests, the wedge test, a variation of ASTM D 3762 and DIN 65 448, has to be performed on all samples except for panels with auto adhesive PUR core materials. In this test two pieces with a dimension of 20 x 100mm of the face material are bonded together, using the same type and amount of glue that is used during the production process. A wedge is then pressed between the two faces, causing an initial crack (see fig. 3-4). Then the wedge is loaded with a force of 3N. The load is applied parallel to the gluing line, promoting the crack growth.

Key: / = initial crack length
Δs = crack growth after exposure

fig. 3-4 wedge test for panels with core material glued to faces using adhesives; taken from prEN 14509
The whole setup is then exposed to the following conditions:

<table>
<thead>
<tr>
<th>Temperature</th>
<th>Humidity</th>
<th>Exposure Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>70 °C</td>
<td>in water</td>
<td>24 h</td>
</tr>
</tbody>
</table>

The test is passed when:

- The initial crack does not grow by more than 20mm after load is applied
- The crack does not grow by more than further 20mm after exposure
- The crack does not occur between adhesive and facing material

The wedge test is also discussed in Berner et al. (1994). This test can predominantly be seen as quality evaluating. The results presented in Berner et al. (1994) indicate that samples either pass the test or clearly fail. Adhesion failure always occurred in failing samples. For the purpose of this research, which tries to contribute to a quantitative approach on durability evaluation, the wedge test is not considered further.

### 3.4.2.5 Evaluation of other degradation effects

#### Long-term loading

Long-term loads occur in roof panels only. They are dead loads, such as self-weight or snow. The effect of increasing deflection under constant load is called creep and is well understood (Jungbluth and Berner, 1986). There are two testing methods in the standard, both dealing with the problem in the normative Appendix A of the standard.

- A3.6: Long-term loading on short beam under shear
- A6: Determination of creep coefficient, long-term load test on full panel

Both tests are well understood and widely accepted. They do not require further discussion.

#### Point and access loads

In prEN 14 509 Chapter 5.2.3.2, “Resistance to point loads and access loads – ceiling panels,” deals with the problem of roof panels that are accessible. In annex A.9.1 and A.9.2 two test
methods, evaluating the ability of a sandwich panel to withstand occasional and repeated access, are described. Recent research (ASPA, 2004) has shown that particularly mineral wool core panels are sensitive to point and access loads. Repeated loading on the same spot leads to local crushing of the core, destroying the connection between panel face and core. Plastic foam core panels have shown to be rather insensitive to this kind of loading. It was found that the proposed test methods in prEN 14509 are well suited to predict the capability of a panel configuration to handle such loads. When comparing to in-situ testing correlation was high. This kind of loading, however, is not within the scope of this work. It is only mentioned for completeness.

From the short outlook on the actual version of the standard (that is, however, still subject to discussion in some parts), it becomes clear that the durability evaluation of sandwich panel construction is:

a) important because it has its own comprehensive chapter (Annex B, which is normative) and the results are directly stated on the CE label; and
b) there are a number of tests with a number of possible outcomes and ways to either pass or fail the test.

The background for all pass and fail criteria in the tests mentioned in 3.4.2 is to control the slope of the resistance curve, which decreases over time, as illustrated in figure 3-2.

With sandwich panels there are two fundamental problems when evaluating durability, namely:

1. For one basic property (wrinkling), it is not possible to expose the specimen to accelerated ageing conditions and then do the testing because the required samples are simply too big. It has been widely agreed that, as it is not possible to determine the wrinkling strength in such a way, other parameters can be evaluated instead. This is also common practice for other materials. For sandwich panels, it is generally accepted that it is sufficient to take the tension capacity of a small scale sample. On the one hand, the test is easy to perform, it is standardised, and it gives a good impression on the integrity of the whole sandwich structure. On the other hand, there is no knowledge what impact a decreasing tension capacity has on the wrinkling strength of a whole panel.
The tension capacity itself is indeed never needed when designing a sandwich panel. Other design parameters currently stay unchecked though it is rather obvious that durability affects all design parameters.

2. If accelerated ageing tests with elevated temperatures are performed, typical temperatures for artificial climates start at about 70°C and, in more or less equal steps, go up to 320°C (DIN ISO 2578). For typical foams used in sandwich panels, the possible temperature range ends at a little more than 90°C. At higher temperatures the plastic foams, which is the most important product group when looking at core materials, simply disintegrate or liquefy. This leaves very little possibilities for temperature variations. Some other core materials, such as mineral wools, are hardly sensitive to temperature at all but can be damaged by increased levels of humidity inside the panel.

The proposed testing DUR 1 to DUR 3 can, therefore, only be seen as a temporary solution. They are intricate and need to be simplified and re-evaluated to allow an accurate and effective durability evaluation. It is desirable to find a correlation between tension capacity and other more important material properties.

3.4.3 ASPAN durability research

A research programme sponsored by the European Union, dealing with the problem of evaluation of durability for sandwich panels, was undertaken. The project was called “ASSPAN - Durability Assessment of Sandwich Panels intended to be used for Roof Covering and Wall Finishes (GRD2-2000-30043).” It was situated in the 5th framework of the Union’s research funding under the “competitive and sustainable growth programme.” Participants in the project were:

- University of Manchester; Manchester; UK
- EPIC; London; UK
- CSTB; Marne-la-Valle; F
- Fachhochschule Mainz; Mainz; D
- Tampere University of Technology; Tampere; FIN
- ICITE-National Research Council; Milan; I
- Paroc Oy Ab; Parainen; FIN
- Centro de Investigacion Tecnologica; Azpeitia; E
The project started in January 2002 and ran until the spring of 2004. It focused on the following key aspects, dealing with sandwich panel durability:

- It investigated the “in life” performance of sandwich panels. As ageing in rigid foam cores can only be caused by chemical changes, these were also studied further (scope of author’s work within programme).
- Different core materials were tested under a variety of artificial climates. Here, only tension testing was performed (participation of the author within the programme).
- Other simpler accelerated durability test methods were meant to be derived from these tests. The testing procedures should have been enlarged to offer appropriate solutions for southern European countries (thermal shock test on sandwich panels simulating solar radiation peaks and rain shock situations).

Despite this, there were other tasks within the project (fire resistance testing, walkability testing and deterioration of insulation values) that were worked on but these tasks have no influence on this project and are, therefore, omitted here.

The most useful information from the ASPAN research to this work is the outcome of a large number of tensile tests on specimen of a variety of different core materials that were subjected to many different artificial climates prior to testing.

There are, however, shortcomings in the research programme. The biggest shortcoming of the ASPAN research is that no connection between the evaluated tension capacity and other more important material properties was established. It will, therefore, be problematic for the project to derive criteria for durability evaluation. If, as it is at the moment state of the art, a drop in tension capacity of up to 60% is considered to be an acceptable decline, why is the wrinkling strength, which is derived from a full scale test on a new panel under ambient conditions, not lowered accordingly? The same is true for other material properties, such as compression capacity, which may be crucial at supports and under point loads or shear capacity. The shear modulus, as one of the most influencing factors when calculating the deflection of sandwich panel structures, remains unchanged for the design. The shear modulus again is determined on new samples under laboratory conditions. Changes over time are currently not accounted for.
3.4.4 Other research

Extensive research at the Tampere University of Technology has been undertaken (Reentilä, 2003). The work, however, concentrates on the ageing of bonding for mineral wool core sandwich panels utilizing adhesive bonding systems. The work presents a mathematical model, which incorporates test results of artificial ageing scenarios. Result is an ageing model, allowing predicting losses in strength for cross panel tensile strength under different climatic impacts. Here again, it is the cross panel tensile strength that is used to indicate the over all strength of the sandwich panel. The work is missing a statement on the effect of loss in tensile strength on other, more important mechanical parameters. The model is based on the assumption that ageing, meaning the loss in tensile strength, can be described using a logarithmic or power law type trend-line. Such trend-lines are generated on the base of experimental results after exposure to a variety of different ageing scenarios. The scenarios differ in humidity and temperature level, as well as in exposure time. With the help of the generated model it is possible to compare deterioration speeds at different temperature and humidity combinations. In this research, the model will, for the first time, be applied to actual “in panel” climates, thus allowing calculating the acceleration factor for any temperature and humidity combination in artificial ageing of mineral wool.

This may lead to acceptable correlation factors for mineral wool cores. Unfortunately, this is not so for polymeric core materials, such as polyurethane, where the decrease in tensile strength does not follow a meaningful, mathematically specifiable curve.

Earlier research on polyurethane based core materials (Just, 1995) has shown that the degradation process does not only affect cross panel tensile strength. Just (1995) tested panel shear strength after exposure to artificial climates and also found changes here. The number of tests described in this report is, however, limited.
4 Testing Methodology and Test results

In most areas this research relies on established tests for sandwich panels as described in prEN 14509 or ECCS (2000). This includes standardized tests, such as cross panel tensile tests, compressive tests, and small scale shear tests. These tests are, however, not sufficient in describing the deterioration of all relevant mechanical properties. A small scale test investigating the wrinkling strength is, therefore, proposed. Such small scale wrinkling test shall give comparable values to those obtained in a full scale test. The full scale test, when performed as a six point bending test, causes a local deformation at the area of load introduction. This effect superimposes with bending stresses and thus causes a combined load action. Such effect is investigated and taken into account for the development of the small scale test on wrinkling strength.

All small scale tests include pre-ageing and post-ageing investigations. This offers the possibility to determine the influence of the ageing process on all relevant properties. Deterioration, although at a lower speed, also happens in reality. Old panels have, therefore, been collected and tested to determine the remaining panel strength at the end of their lifetime. Regular investigations on panels that are mounted in an outdoor testing rig provide information on real panel excitation and changes in elasticity. Together with the results of numerous cross panel tensile tests on aged samples, a possible relationship between natural ageing and accelerated laboratory ageing can be found.

4.1 Established sandwich panel tests

For completeness, the established tests are briefly described in the following. The presented tests are well established and do not impose a significant expenditure for laboratories or panel producers that deal with sandwich panel testing on a regular base.

4.1.1 Cross panel tensile test

Cross panel tensile testing was performed in accordance with prEN 14509 annex A.1. Before testing, all samples were brought to normal condition by being stored under laboratory conditions for at least 24 hours. When the samples were subject to artificial ageing, their weight was measured and only when the change in weight after 24 hours was below 1 percent, the samples were admitted for testing. This procedure was also adopted for compression,
shear, and small-scale wrinkling tests. Samples for tensile testing were cut to a nominal size of 100mm x 100mm x nominal thickness. This is also true for mineral wool core panels although bigger samples may lead to more homogeneous results. The test specimens were sampled by cutting sandwich stripes at panel width, which were then cut down to the required cuboid size. It was ensured that a set of specimen contained samples from more than one stripe. Accurate cutting plans were drawn making backtracking of individual samples possible. All panels sharing the same name in this research came from the same production batch. Only such a sampling method ensures comparability.

The testing was performed with panel faces in place. All testing was performed in the same Zwick universal testing machine type 1455. Before testing, two 5 mm steel plates were glued to the samples faces using PMMA glue. The use of plywood was renounced as the effect on determination of E-modulus is uncertain. Specimens were loaded at a constant displacement rate of 2 % of the initial thickness per minute. The displacement was measured directly at the sample in order to ensure accurate determination of E-modulus. The load – displacement curve was drawn and the ultimate load together with the failure mode was recorded. The ultimate tensile strength ($f_{ct}$) is then given by:
where

\[ F_u: \] ultimate load in test
\[ A: \] measured plane area of sample tested

The tensile E-modulus \((E_{ct})\) was determined on the lower half of the stress – strain curve using the following equation:

\[ E_{ct} = \frac{\Delta \sigma}{\Delta \varepsilon} \]

where

\[ \Delta \sigma: \] difference in stress at two points in stress – strain curve
\[ \Delta \varepsilon: \] affiliated difference in strain \((\Delta l/l)\) at two points in curve

All samples were tested with their faces in place. This means that cross panel tensile strength not only checks tensile strength of the core but also strength of the bond between face and core, as well as all other layers in the panel cross section. The weakest link, where the failure occurs, determines the ultimate strength.

### 4.1.2 Compressive strength of core

The compressive strength of the core material was determined in accordance with prEN 14 509 annex A.2. All samples were of size 100mm x 100mm x nominal thickness. The tests were displacement-controlled at a speed of 2% of the initial thickness per minute. The load – displacement curve was drawn and again the displacement was taken directly at the test specimen, minimizing errors when calculating the elastic modulus. The maximum load was recorded. As all samples did not show a defined failure point in the load – displacement curve, the tests were aborted when reaching 10% relative deformation. The corresponding load was taken as the ultimate load.
The ultimate compressive strength is then given by:

\[
eq 4.1-3 \quad f_{\text{cc}} = \frac{F_u}{A}
\]

where
- \(F_u\): ultimate load in test
- \(A\): measured plane area of sample tested

The compressive E-modulus was determined, using two points at the lower half of the stress - strain curve. Calculation of the compressive E-modulus was then undertaken using:

\[
eq 4.1-4 \quad E_{\text{cc}} = \frac{\Delta \sigma}{\Delta \varepsilon}
\]

where
- \(\Delta \sigma\): difference in stress at two points in stress - strain curve
- \(\Delta \varepsilon\): affiliated difference in strain \((\Delta l/l)\) at two points in curve

### 4.1.3 Shear test on core material

A four point bending test was used to determine the shear strength and shear modulus of a sandwich panel core material. The test was in accordance with prEN 14509 annex A3. All samples were of size 1000mm x 100mm x nominal thickness of panel. The span length was 700 mm for all samples. All tests were undertaken with panel faces in place. The samples were taken from the lengthwise direction of the panel. In order to avoid local crushing of the core, metal load-spreading plates were used (see fig. 4-2). The loading was increased controlling the displacement at a rate of 15 mm/min. The displacement at mid span was constantly measured and recorded until shear failure occurred. The ultimate load \((F_u)\) was recorded together with the mode of failure. The shear distribution in the core is of rectangular shape. The shear load from the faces is directly transferred to the core. The ultimate shear strength of a core material \((f_{\text{cv}})\) is, therefore, given by:

\[
eq 4.1-5 \quad f_{\text{cv}} = \frac{F_u}{2 \cdot B \cdot e}
\]

where
- \(F_u\): ultimate load in test
- \(B\): measured width of specimen
- \(e\): measured depth between centroids of faces
The shear modulus of the core material was determined from the straight part of the load-deflection curve, subtracting bending deflection from total deflection as follows. For this, the flexural rigidity ($B_s$) was determined:

\[ B_s = \frac{E_{p1} \cdot A_{p1} \cdot E_{p2} \cdot A_{p2} \cdot e^2}{E_{p1} \cdot A_{p1} + E_{p2} \cdot A_{p2}} \]

where

- $E_{p1}$: E-modulus of the top face
- $A_{p1}$: measured area of the top face
- $E_{p2}$: E-modulus of the bottom face
- $A_{p2}$: measured area of the bottom face

Knowing that the plain core of a sandwich panel has negligible bending stiffness, the bending part of the total deflection ($\Delta w_b$) is given by:

\[ \Delta w_b = \frac{\Delta F \cdot L^3}{56.34 \cdot B_s} \]

where

- $\Delta F$: difference in loading between two relevant points on load-deflection curve
- $L$: span of the test specimen

The part of the total deflection caused by shear ($\Delta w_s$) is therefore:

\[ \Delta w_s = \Delta w - \Delta w_b \]

Knowing this, the shear modulus of the core ($G_c$) can be determined through:

\[ G_c = \frac{\Delta F \cdot L}{6 \cdot B \cdot d_c \cdot \Delta w_s} \]

where

- $d_c$: measured depth of the core material
4.1.4 Wrinkling test on full scale panel

The wrinkling strength is defined as the ultimate load, a panel face can take in compression before it fails in buckling. The compression in the panel face is, in practice, induced by a bending moment that can, for example, be caused by wind loads. The full scale wrinkling test simulates such loading. Determining the wrinkling stress of a sandwich panel generally requires full scale testing, although small scale testing substituting this large scale test will be presented in chapter 4.2. The full scale test was carried out by subjecting a simply supported beam to four line loads. The sample length must be chosen, so as to guarantee a wrinkling failure in the tests. PrEN 14509 provides a guidance table, showing what minimum length (\(l\)) should be chosen depending on the total depth of the panel (\(d\)) to achieve wrinkling failure.

\[
\begin{array}{ccc}
\text{d} & \leq & 40\text{mm} \\
40 & < & d & \leq & 60\text{mm} \\
60 & < & d & \leq & 100\text{mm} \\
d & > & 100\text{mm} & \quad & l = 6.0\text{m}
\end{array}
\]

If a too short length is chosen, the panel is likely to fail in shear instead of wrinkling.

All samples are then of the size \(L\) x nominal width x nominal thickness. In many cases, wrinkling failure is also achieved with smaller lengths. This also depends on the geometry of the panel face, the thickness of the face material, and the mechanical properties of the core.
When undertaking the test it is important to mark the top or bottom side during production. Particularly in foam cored panels, the density in the panel cross sections varies between top and bottom face. This is caused by the production procedure, where the mixed but still liquid PU mix is spread on the bottom face and then rises to the top face while polymerizing. Generally, homogeneity is better at the bottom face. The cavitation found on this side of the foam is limited. Often this results in better bonding between core and face. While for design procedures generally both faces are tested for determination of wrinkling strength and the lower value is considered as decisive, in this research only the bottom face was tested. This minimizes the scatter of results, particularly when comparing full scale to small scale test results. For the purpose of durability, it is particularly important to know the relative change of properties over time. Therefore, it is not important which face of the panel is chosen for evaluation as long as consistent results are compared. The tests were undertaken displacement-controlled at a speed of 12 mm/min. The deflection in two points at mid-span was recorded. A load deflection curve was drawn and the ultimate load \( (F_u) \), together with the mode of failure, was recorded.

In a test setup according to figure 4-3 the ultimate bending moment \( (M_u) \) is given by:

\[
M_u = \frac{F_u \cdot L}{8}
\]

where

- \( F_u \): ultimate load including self weight of panel and loading equipment
- \( L \): span of test specimen

For flat or lightly profiled panels the wrinkling stress is then given through:

\[
\sigma_w = \frac{M_u}{e \cdot A_i}
\]

where

- \( e \): depth between centroids of faces
- \( A_i \): cross-section area of the face in compression

For the correct evaluation of the test, it is important to determine the accurate panel geometry and thickness of faces. Only with this information can the depth between the centroids of faces \( (e) \) be determined exactly.
fig. 4-3 six point bending test determining wrinkling strength of sandwich panel. Note that failure usually occurs at inner line of loading where local deformation and maximum bending moment interact.

### 4.2 Small scale wrinkling test

All mechanical parameters necessary for sandwich design can be obtained from small scale testing. Sole exception is the wrinkling strength. For a durability research this poses the problem that it is not possible to determine the wrinkling strength after artificial ageing. A small scale test setup determining wrinkling strength has therefore been developed. When developing a small scale wrinkling test for sandwich panels, it is the general idea to no longer induce compressive stresses in the face through a bending moment but cut out a small panel area and expose it to a direct load in plain direction. Baehre (1988) and Pfeiffer (2000) have previously tried to establish small scale wrinkling tests for sandwich panels. However, it was not possible to determine the exact wrinkling capacity of a sandwich panel through small scale testing. The main problem of the earlier work was in finding a way of introducing the in plain loads without damaging the thin panel face locally, a problem that does not occur with the full scale test. Special load application devices help to overcome the problem. During the test series it has been found that the full-scale bending test loads the sandwich panel twofold. In the upper face, the in-plane bending stress meets the deformation caused by the line loads, which evoke the actual bending stress. For a direct comparison between six point bending test and a small scale shear test, this load combination must not be neglected. The results gathered in this project suggest that the research conducted by Baehre (1988) would have had a positive outcome if he had taken the local deformations into consideration. With the results he
had on hand, it was not possible to find a small scale test defining the wrinkling strength in the same way a full scale test does.

Nevertheless, Baehr (1988) has shown that tendencies of changes in wrinkling behaviour can be determined with the help of small scale tests. Simple small scale wrinkling tests have also been employed in the author’s earlier work (Pfeiffer, 2000) showing that small scale wrinkling tests can be used to determine the influence of poor cross panel tensile strength on wrinkling strength. The tests used then were, however, rudimentary. Hence, a new small scale test, determining wrinkling strength, was developed for the purpose of this research.

4.2.1 Test setup

The new test combines two previously used test methods. The idea behind all small scale wrinkling tests is that in the regular bending test, as described in chapter 4.1.4, the upper face is under compression while the lower face is under tension. Instead of causing compression in the upper face through a bending moment, the small scale test directly puts force on one face, loading it in a vertical, in-plane direction (see fig. 4-5). While the author in his earlier work used a wooden T-shaped load application device, which was glued to a rectangular specimen with completely flat faces causing compression in one face, Baehr (1988) used a micro-profiled specimen with T-shaped load application devices made of steel. The load application device was not glued to the specimen but rather clipped onto it. In both cases the T-shaped device was chosen to gradually introduce the load to the specimen without causing local failure at the point of loading (see fig. 4-4).
While the author of this text did not compare the results from the small-scale tests to the full-scale tests, Baehre failed to find a small-scale test, giving similar results as obtained from a full-scale bending test. The reason for this failure that Baehre did not consider the local deformation in the compressed face under the loading points in the full scale test. Such deformation weakens the observed wrinkling strength as they cause an extra moment and such extra stresses in the face. For a small scale tests comparable to a full scale test this effects must be accounted for.

For this work, a combination of the two previously described small-scale tests, determining wrinkling strength, was chosen. The profiled specimen from Baehre was enlarged to a bone-shaped sample, again using T-shaped load application devices at both ends of the specimen. This time the application devices were both, glued and clamped to the samples. Only the combination of gluing and clamping together with the bone shape hinders the specimen from failing early through local crushing.

Gluing the load application device to the samples allows the load to be introduced to the panel faces over a larger surface area, reducing concentrated load effects. Some load is introduced through shear force in the glued area; some through direct loading at the top and bottom end, where the specimen touches the T-shaped device (see fig. 4-6).
fig. 4-6 forces at load application device. Note that for illustration purposes specimen is separated from load application device. Total force \( F \) is transferred to specimen directly \( (F_{\text{direct}}) \) and through shear forces in adhesive layer \( (F_{\text{shear}}) \). The clamp device connects the load application device with the specimen.

To study the effect of the local deformation at the load introductory places occurring in the full scale test, samples with and without local deformations were studied. A three step approach was taken. First samples with completely even faces were tested, giving the maximum wrinkling strength that can be obtained. In a second step the faces were dented prior to executing the small scale test. The depth of the imprinted deformations was of the same dimensions as observed in the full scale test. In a third step the effect was simulated through a bi-axial loading in the small scale test. An additional load device was clamped to the specimen loading it in a perpendicular direction. All obtained results were compared to the full scale bending test.

4.2.2 Calibration of test setup

In order to calibrate the test setup, a test series, comparing large-scale and small-scale testing of wrinkling strength, was undertaken. All specimen tested in this series were taken from the same production batch. Full panels were first tested as simply supported beams as described in chapter 4.1.4. The tested panels had a PUR core between two steel faces. After cleaning the face from its organic coating, paint and the zinc layer, the remaining net thickness was measured at 0.59 mm for one face and 0.44 mm for the other face as an average. As the
thicker face showed a more homogeneous core structure (lower side of production), this side was chosen for the test. Reason for this course of action was to improve chances of correlation. The span of the tested specimen in the full scale test was 5000 mm. The panels were tested in a deflection-controlled test setup at a speed of 12 mm/min. The following results were obtained:

<table>
<thead>
<tr>
<th>FULL SCALE BENDING</th>
<th>Test 1</th>
<th>Test 2</th>
<th>Test 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>maximum load (F)</td>
<td>16792 N</td>
<td>16710 N</td>
<td>16714 N</td>
</tr>
<tr>
<td>distance between centroids of faces</td>
<td>98.13 mm</td>
<td>97.93 mm</td>
<td>97.93 mm</td>
</tr>
<tr>
<td>width of panel</td>
<td>1000 mm</td>
<td>1000 mm</td>
<td>1000 mm</td>
</tr>
<tr>
<td>thickness of face</td>
<td>0.59 mm</td>
<td>0.59 mm</td>
<td>0.59 mm</td>
</tr>
<tr>
<td>maximum moment</td>
<td>10.4950 kNm</td>
<td>10.4437 kNm</td>
<td>10.4462 kNm</td>
</tr>
<tr>
<td>maximum stress in face</td>
<td>181.27 N/mm²</td>
<td>180.75 N/mm²</td>
<td>180.80 N/mm²</td>
</tr>
<tr>
<td>failure mode</td>
<td>wrinkling</td>
<td>wrinkling</td>
<td>wrinkling</td>
</tr>
</tbody>
</table>

The average wrinkling strength of the tested panel face was, therefore, 180.94 N/mm². The same type of panel was then tested in a small scale wrinkling test. The nominal dimensions and accurate test setup is illustrated in figure 4-7 and can also be seen in figure 4-4.
The test was undertaken at a constant cross head speed of 1 mm/min. Failure occurred after a testing time of approximately 1 minute. The cross-head speed is a crucial factor for this test setup, as relatively high loads need to be reached at relatively small deformations. Testing machinery, controlling cross-head speed with the help of a turning spindle, is suitable for this purpose. The following test results were obtained:

**Table 4-2 Test Results of Small Scale Wrinkling Test on Just Made Samples**

<table>
<thead>
<tr>
<th>SMALL SCALE WRINKLING</th>
<th>Test 1</th>
<th>Test 2</th>
<th>Test 3</th>
<th>Test 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Width of bone shaped sample</td>
<td>201.40 mm</td>
<td>201.21 mm</td>
<td>201.44 mm</td>
<td>200.77 mm</td>
</tr>
<tr>
<td>Thickness of face</td>
<td>0.59 mm</td>
<td>0.59 mm</td>
<td>0.59 mm</td>
<td>0.59 mm</td>
</tr>
<tr>
<td>Maximum load</td>
<td>27120 N</td>
<td>26480 N</td>
<td>27200 N</td>
<td>27808 N</td>
</tr>
<tr>
<td>Wrinkling strength</td>
<td>228.23 N/mm²</td>
<td>223.06 N/mm²</td>
<td>228.86 N/mm²</td>
<td>234.76 N/mm²</td>
</tr>
<tr>
<td>Failure mode</td>
<td>wrinkling</td>
<td>wrinkling</td>
<td>wrinkling</td>
<td>wrinkling</td>
</tr>
</tbody>
</table>
The wrinkling capacity, obtained from the small scale test, averages to 228.73 N/mm². The standard deviation of 4.79 is very low. When compared with the full scale test, however, an increase of 26.4% is found. This difference is not acceptable if determination of accurate wrinkling strength is required.

The reason for the observed difference lies in the test setup of the full scale bending test. In a six point bending test the load is transferred to the panel in four line loads (see fig. 4-3). At the point of load introduction, this results in deformation of the face. Because of this, the specimen usually fails at the inner point of loading, where maximum deformation and maximum moment interact.

![Diagram of six point bending test](image)

**fig. 4-8** Local deformation under point of loading causing early failure in six point bending test. The discontinuity (d) occurs under all loading points but interacts with maximum bending moment at indicated point.

The results of a six point bending test are considered to be conservative. However, the obtained results are homogeneous, as the production related face deformation is always overlaid by the local deformation under the point of load introduction.

In order to achieve the same results of small scale testing as determined through full scale testing, this deformation effect needs to be taken into account. In a first step this is done by
denting the panel face at a depth \((d)\), similar to the deformation caused in the full scale test. It was found that for the particular panel used in this test series the deformation at maximum load was approximately 0.9 mm. In order to evaluate the effect of denting the panel face prior to testing in the small scale apparatus, samples with a deformation of approximately 0.9 and 1.4 mm were tested. The following results were obtained:

<table>
<thead>
<tr>
<th>SMALL SCALE WRINKLING</th>
<th>Unit</th>
<th>Test 1</th>
<th>Test 2</th>
<th>Test 3</th>
<th>Test 4</th>
<th>Test 5</th>
<th>Test 6</th>
</tr>
</thead>
<tbody>
<tr>
<td>depth of dent ((d)) mm</td>
<td>~0.9</td>
<td>~0.9</td>
<td>~0.9</td>
<td>~1.4</td>
<td>~1.4</td>
<td>~1.4</td>
<td></td>
</tr>
<tr>
<td>width of bone shaped sample mm</td>
<td>~200</td>
<td>199.36</td>
<td>199.87</td>
<td>200.87</td>
<td>199.67</td>
<td>200.05</td>
<td></td>
</tr>
<tr>
<td>thickness of face mm</td>
<td>0.59</td>
<td>0.59</td>
<td>0.59</td>
<td>0.59</td>
<td>0.59</td>
<td>0.59</td>
<td></td>
</tr>
<tr>
<td>maximum load N</td>
<td>&gt;9000</td>
<td>13872</td>
<td>15328</td>
<td>10720</td>
<td>11488</td>
<td>9592</td>
<td></td>
</tr>
<tr>
<td>wrinkling strength N/mm(^2)</td>
<td>&gt;76</td>
<td>117.94</td>
<td>129.98</td>
<td>90.45</td>
<td>97.52</td>
<td>81.27</td>
<td></td>
</tr>
<tr>
<td>failure mode</td>
<td>wrinkling wrinkling wrinkling wrinkling wrinkling wrinkling</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Omitting the first test, that fails to deliver accurate test data due to machine problems, the found wrinkling strength averages to 123.96 N/mm\(^2\) for the samples with a 0.9 mm deformation. In comparison with the full scale test, the determined wrinkling strength is 68 \% of the wrinkling strength found in the full scale test. For the bigger dents at 1.4 mm, the results are even lower, as had been expected. The calculated wrinkling strength averages to 89.75 N/mm\(^2\), which is 49 \% of the strength obtained from a full scale test.

Pre-deforming the face through denting is therefore thought to be too severe. To obtain the deformations for this test setup, the samples were dented by putting them on a rigid surface and loading them with a force, corresponding to the force needed for the full scale test:

Average maximum load \((F_{\text{max}})\) from full scale test: 16739 N

Average deformation load for small scale specimen \((F_{\text{def}})\) employing same application plates:

\[
F_{\text{def}} = \frac{F_{\text{max}}}{4} \cdot \frac{b_{\text{bone}}}{b_{\text{full scale}}} = \frac{16739[N]}{4} \cdot \frac{200[mm]}{1000[mm]} = 837[N]
\]

where
After loading the panel with this force, no plastic deformations were detected. This means that, during the full scale test, the deformation is rather elastic. A permanent dent is only found under a loading, well exceeding the load transferred in the full scale test. Because of this, taking the local deformation into account through denting is a procedure, which is too severe as can be seen from the results in table 4-3.

In a next step, an additional loading device was introduced to the test. This additional device loads the panel perpendicular to the faces, causing the same deformation as obtained in the full scale test.

The load is applied through two steel profiles, having the same dimensions as the ones used in the full scale test. The loading is controlled with the help of two screws and measured in a load cell. In a first setup (a) the additional load device was supported by an additional beam.

![Diagram of the test setup](image)

**fig. 4-9 small scale wrinkling test with combined load configuration loading sample in bi-directional manner.**
on the back of the specimen (see fig. 4-9). In a second setup (b) the additional load device was clamped directly to the specimen. The following results were obtained:

<table>
<thead>
<tr>
<th>SMALL SCALE WRINKLING</th>
<th>Test 1</th>
<th>Test 2</th>
<th>Test 4</th>
<th>Test 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unit</td>
<td>a</td>
<td>a</td>
<td>b</td>
<td>b</td>
</tr>
<tr>
<td>Load in deformation device</td>
<td>N</td>
<td>837</td>
<td>837</td>
<td>837</td>
</tr>
<tr>
<td>width of bone shaped sample</td>
<td>mm</td>
<td>199.98</td>
<td>199.97</td>
<td>201.70</td>
</tr>
<tr>
<td>thickness of face</td>
<td>mm</td>
<td>0.59</td>
<td>0.59</td>
<td>0.59</td>
</tr>
<tr>
<td>maximum load</td>
<td>N</td>
<td>16720</td>
<td>17296</td>
<td>21072</td>
</tr>
<tr>
<td>wrinkling strength</td>
<td>N/mm²</td>
<td>141.71</td>
<td>146.60</td>
<td>177.07</td>
</tr>
<tr>
<td>failure mode</td>
<td>-</td>
<td>wrinkling</td>
<td>wrinkling</td>
<td>wrinkling</td>
</tr>
</tbody>
</table>

The average wrinkling strength obtained with setup (a), is 80 % of the strength observed in the full scale test. The reason for this is an extra bending stress on the test specimen caused by the additional load device. In a first step this setup was chosen to hinder the back face of the sample from denting. As only one face is tested in this setup, denting of the back face has almost no effect on the wrinkling strength of the loaded face. The results obtained from setup (b) show very good correlation with the full scale bending test. When comparing the average results, 98.8 % of the strength determined in the full scale bending tests is reached. This shows clearly that it is possible to use small scale testing to determine the accurate wrinkling strength of a sandwich panel. It is, however, necessary to simulate the full scale test accurately and to take even small details, like the local deformations at the load introductory plates into account.

When lacking knowledge of the maximum load obtained in the full scale test ($F_{max}$), which is the case when no full scale test has been carried out on a particular panel, it is necessary to gradually increase the deformation load relative to the load parallel to the face. The load needed on the deformation device can be calculated on the base that the stress parallel to the face is equal for both tests. This means, that a certain load in the small scale test, corresponds to a certain load in the full scale test, both causing the same tresses parallel to the surface. At the same time this load determines the load on the additional load device and can be calculated as described in the following:
The stress in the examined flat face in the six point bending test is given by

\[ \sigma_{\text{f6p}} = \frac{F_{\text{f6p}} \cdot l}{8 \cdot e \cdot A_{\text{f6p}}} \]

where

- \( \sigma_{\text{f6p}} \): stress in face in 6 point bending test
- \( F_{\text{f6p}} \): total load on panel in 6 point bending test
- \( l \): length of system
- \( e \): distance between centroids of faces
- \( A_{\text{f6p}} \): cross section area on pressed face in 6 point bending test

and the corresponding stress in the small scale test is given by

\[ \sigma_{\text{fsc}} = \frac{F_{\text{fsc}}}{A_{\text{fsc}}} \]

where

- \( \sigma_{\text{fsc}} \): stress in face in small scale wrinkling test
- \( F_{\text{fsc}} \): total load on panel parallel to face in small scale wrinkling test
- \( A_{\text{fsc}} \): cross section area on pressed face in small scale wrinkling test

Simulating the full scale test through the small scale test requires an equal stress parallel to the face (wrinkling strength). Equating equation 4.2-1 and equation 4.2-3 and solving against \( F_{\text{f6p}} \) while agreeing on

\[ A_{\text{f6p}} = t \cdot b_{\text{f6p}} \]
\[ A_{\text{fsc}} = t \cdot b_{\text{fsc}} \]

where

- \( t \): net thickness of face
- \( b_{\text{f6p}} \): width of panel in 6 point bending test
- \( b_{\text{fsc}} \): width of sample in small scale wrinkling test

leads to

\[ F_{\text{f6p}} = \frac{8 \cdot F_{\text{fsc}} \cdot e}{l} \cdot \frac{b_{\text{f6p}}}{b_{\text{fsc}}} \]

which can also be written as

\[ F_{\text{f6p}} = \frac{2 \cdot F_{\text{fsc}} \cdot e}{l} \cdot \frac{b_{\text{f6p}}}{b_{\text{fsc}}} \]

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Looking now at the stresses induced by the test setup (loading perpendicular to the faces), these can be written as

\[ \sigma_{\text{def/6P}} = \frac{F_{\text{SP}}}{4 \cdot b_{\text{SP}} \cdot B} \quad \text{for the full scale test} \]

and

\[ \sigma_{\text{def/SC}} = \frac{F_{\text{def}}}{b_{\text{SC}} \cdot B} \quad \text{for the small scale test} \]

where

- \( \sigma_{\text{def/6P}} \): stress under point of load introduction in full scale test
- \( \sigma_{\text{def/6P}} \): stress under additional load device in small scale test
- \( F_{\text{SP}} \): total load on full scale test
- \( F_{\text{def}} \): load introduced by additional load device in small scale test
- \( B \): width of load application device; equal devices are used in both setups

For comparability of the two tests, these stresses need to be equal. Solving against the deformation load for the small scale test leads to

\[ F_{\text{def}} = \frac{F_{\text{SP}} \cdot B \cdot b_{\text{SC}}}{4 \cdot B \cdot b_{\text{SP}}} \]

combining this with eq. 4.2-5 leads to

\[ F_{\text{def}} = \frac{2 \cdot F_{\text{SC}} \cdot e \cdot b_{\text{SP}} \cdot b_{\text{SC}}}{l} = \frac{2 \cdot F_{\text{SC}} \cdot e}{l} \]

The load in the additional deformation device can now be calculated, depending on the axial loading of the sample, the depth between the centroids of the two panel faces, and the length of the static system in the six point bending test.

It was the purpose of this research to find a small-scale test, allowing an evaluation of the change of wrinkling strength over time. It is not the purpose of this test setup to accurately simulate a full scale bending test though this is possible as demonstrated with the obtained
results. It can even be asked if, from a researcher's point of view, the 6-point bending test is an accurate test to determine the wrinkling strength of a sandwich panel. The test harms the panel in a way, which is generally not taken into consideration when evaluating wrinkling strength mathematically. Nevertheless, the test is suitable for practical application as the deformation caused by the test setup overlays production-related deformations, which can vary depending on hardly controllable circumstances. The test is, therefore, considered to be a conservative approach.

For this research, as it only considers durability related changes and thus relative values, it was decided to proceed with a test setup lacking the additional deformation device which makes the test easier to conduct.

### 4.2.3 Results

The test results, obtained after artificial ageing on small scale bone shaped samples, are presented in appendix 1. The obtained results are evaluated in chapter 6.

The results presented here indicate that the small scale wrinkling test is a very good test for estimation of wrinkling strength but requires extensive test preparation such as bone shape cutting and gluing of the load application devices. Laboratories dealing with sandwich panel technology on a regular base can adopt the test with some extra work but panel producers will avoid using the test as it is not required in the code and can at the moment not officially substitute the full scale test. Further testing, underpinning the results obtained here is needed.

### 4.3 Testing after artificial ageing

A variety of core materials under different climates was studied in this research. In general, the relative remaining capacity or modulus is given as an ageing indicator. The remaining capacity (\(C_R\)) can then be written as

\[
eq 4.3-1 \quad C_R = \frac{R_t}{R_0} \cdot 100
\]

where \(R_0\) is the initial resistance of a test family (same batch of samples) and \(R_t\) is the remaining resistance after a period of \(t\) days.
4.3.1 Objectives

It was the aim of the accelerated test regime to study the influence of different climates and different exposure times on the mechanical performance of a sandwich structure. In general, this was done through cross panel tensile testing. Knowing that temperature is the deciding ageing factor for a polyurethane core, a complete test series including tensile, compression, shear, and small scale wrinkling tests was conducted for a particular foam.

4.3.2 Overview of tests conducted

The following test matrix of samples, exposed to artificial ageing conditions, was conducted in this research:

<table>
<thead>
<tr>
<th>No.</th>
<th>Core material</th>
<th>Ageing Condition</th>
<th>Duration (days)</th>
<th>Type of testing</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Polyurethane \text{n-pentane blown}</td>
<td>90°C, RH&lt;15%</td>
<td>0,7,28,56,90</td>
<td>cross panel tensile</td>
</tr>
<tr>
<td>2</td>
<td>Polyurethane \text{HCFC blown}</td>
<td>90°C, RH&lt;15%</td>
<td>0,7,28,56,90</td>
<td>cross panel tensile</td>
</tr>
<tr>
<td>3</td>
<td>Polyisocyanurate</td>
<td>90°C, RH&lt;15%</td>
<td>0,7,28,56,90</td>
<td>cross panel tensile</td>
</tr>
<tr>
<td>4</td>
<td>Expanded Polystyrene</td>
<td>90°C, RH&lt;15%</td>
<td>0,7,28,56,90</td>
<td>cross panel tensile</td>
</tr>
<tr>
<td>5</td>
<td>Stone Wool, lamella</td>
<td>90°C, RH&lt;15%</td>
<td>0,7,28,56,90</td>
<td>cross panel tensile</td>
</tr>
<tr>
<td>6</td>
<td>Stone Wool, slabstock</td>
<td>90°C, RH&lt;15%</td>
<td>0,7,28,56,90</td>
<td>cross panel tensile</td>
</tr>
<tr>
<td>7</td>
<td>Phenolic Foam</td>
<td>90°C, RH&lt;15%</td>
<td>0,7,28,56,90</td>
<td>cross panel tensile</td>
</tr>
<tr>
<td>8</td>
<td>Glass Wool</td>
<td>90°C, RH&lt;15%</td>
<td>0,7,28,56,90</td>
<td>cross panel tensile</td>
</tr>
<tr>
<td>9</td>
<td>Polyurethane \text{n-pentane blown}</td>
<td>90°C, RH&lt;15%</td>
<td>0,7,28,56,90</td>
<td>cross panel tensile</td>
</tr>
<tr>
<td>10</td>
<td>Polyurethane \text{n-pentane blown}</td>
<td>90°C, RH&lt;15%</td>
<td>0,7,28,56,90</td>
<td>compression test</td>
</tr>
<tr>
<td>11</td>
<td>Polyurethane \text{n-pentane blown}</td>
<td>90°C, RH&lt;15%</td>
<td>0,7,28,56,90</td>
<td>short beam shear test</td>
</tr>
<tr>
<td>12</td>
<td>Polyurethane \text{n-pentane blown}</td>
<td>90°C, RH&lt;15%</td>
<td>0,7,28,56,90</td>
<td>s.c. wrinkling test</td>
</tr>
<tr>
<td>13</td>
<td>Expanded Polystyrene</td>
<td>90°C, RH&lt;15%</td>
<td>0,7,28,56,90</td>
<td>cross panel tensile</td>
</tr>
<tr>
<td>14</td>
<td>Expanded Polystyrene</td>
<td>50°C, RH 80%</td>
<td>0,7,28,56,90</td>
<td>cross panel tensile</td>
</tr>
<tr>
<td>15</td>
<td>Expanded Polystyrene</td>
<td>90°C, RH 80%</td>
<td>0,7,28,56,90</td>
<td>cross panel tensile</td>
</tr>
<tr>
<td>16</td>
<td>Expanded Polystyrene</td>
<td>65°C, RH 100%</td>
<td>0,7,28,56,90</td>
<td>cross panel tensile</td>
</tr>
<tr>
<td>17</td>
<td>Expanded Polystyrene</td>
<td>50°C, RH 90%</td>
<td>0,7,28,56,90</td>
<td>cross panel tensile</td>
</tr>
<tr>
<td>18</td>
<td>Polyurethane \text{n-pentane blown}</td>
<td>90°C, RH&lt;15%</td>
<td>0,7,28,56,90</td>
<td>cross panel tensile</td>
</tr>
<tr>
<td>19</td>
<td>Polyurethane \text{n-pentane blown}</td>
<td>50°C, RH 80%</td>
<td>0,7,28,56,90</td>
<td>cross panel tensile</td>
</tr>
<tr>
<td>20</td>
<td>Polyurethane \text{n-pentane blown}</td>
<td>90°C, RH 60%</td>
<td>0,7,28,56,90</td>
<td>cross panel tensile</td>
</tr>
<tr>
<td>21</td>
<td>Polyurethane \text{n-pentane blown}</td>
<td>65°C, RH 100%</td>
<td>0,7,28,56,90</td>
<td>cross panel tensile</td>
</tr>
<tr>
<td>22</td>
<td>Polyurethane \text{n-pentane blown}</td>
<td>50°C, RH 90%</td>
<td>0,7,28,56,90</td>
<td>cross panel tensile</td>
</tr>
<tr>
<td>23</td>
<td>Polyurethane \text{CO2 blown}</td>
<td>90°C, RH 80%</td>
<td>0,7,28,56,90</td>
<td>cross panel tensile</td>
</tr>
<tr>
<td>24</td>
<td>Polyurethane \text{CO2 blown}</td>
<td>50°C, RH 80%</td>
<td>0,7,28,56,90</td>
<td>cross panel tensile</td>
</tr>
<tr>
<td>25</td>
<td>Polyurethane \text{CO2 blown}</td>
<td>90°C, RH 60%</td>
<td>0,7,28,56,90</td>
<td>cross panel tensile</td>
</tr>
<tr>
<td>26</td>
<td>Polyurethane \text{CO2 blown}</td>
<td>65°C, RH 100%</td>
<td>0,7,28,56,90</td>
<td>cross panel tensile</td>
</tr>
<tr>
<td>27</td>
<td>Polyurethane \text{CO2 blown}</td>
<td>50°C, RH 90%</td>
<td>0,7,28,56,90</td>
<td>cross panel tensile</td>
</tr>
<tr>
<td>28</td>
<td>Stone Wool, lamella</td>
<td>90°C, RH&lt;15%</td>
<td>0,7,28,56,90</td>
<td>cross panel tensile</td>
</tr>
<tr>
<td>29</td>
<td>Stone Wool, lamella</td>
<td>50°C, RH 80%</td>
<td>0,7,28,56,90</td>
<td>cross panel tensile</td>
</tr>
</tbody>
</table>

\text{S.c.} - small scale
<table>
<thead>
<tr>
<th>No.</th>
<th>Core material</th>
<th>Ageing Condition</th>
<th>Duration (days)</th>
<th>Type of testing</th>
</tr>
</thead>
<tbody>
<tr>
<td>30</td>
<td>Stone Wool, lamella</td>
<td>90°C, RH 60%</td>
<td>0, 7, 28, 56, 90</td>
<td>cross panel tensile</td>
</tr>
<tr>
<td>31</td>
<td>Stone Wool, lamella</td>
<td>65°C, RH 100%</td>
<td>0, 7, 28, 56, 90</td>
<td>cross panel tensile</td>
</tr>
<tr>
<td>32</td>
<td>Stone Wool, lamella</td>
<td>50°C, RH 90%</td>
<td>0, 7, 28, 56, 90</td>
<td>cross panel tensile</td>
</tr>
</tbody>
</table>

Tests No. 1 to 9 were undertaken within the ASPAN research. They were part of the workload given to the Fachhochschule Mainz as a project partner.

Tests No. 1-13, as well as No. 18, 23, 28 were exposed in a climate chamber (Heraeus Vötsch 4055) with controllable temperature and humidity at the Fachhochschule Mainz. The temperature was controlled with an accuracy of ± 0.1 °C. Humidity control was turned off, which lead to a very dry climate. Regular control of relative humidity indicated values well below 5 % RH.

Tests No. 13-32 were undertaken on the same batch of panels as they were used in the outdoor testing rig for in situ testing. Samples under condition 50°C, 90 % RH, as well as 50°C, 80 % RH and 90°C, 60 % RH were aged at Tampere University in Finland. The samples under the condition of 65°C and 100 % relative humidity were aged in a tropic box at CSTB in France. All of the testing, however, except for the samples aged in France, was performed in Mainz. Performing tests on the same machinery using standard and well practised test preparation and test realization eliminates laboratory specific discrepancies as have been observed on some occasions during the ASPAN research project.

The tropic box artificial ageing was undertaken in accordance with prEN 14 509 annex B.3, the DUR 2 test described in 3.4.2.2.

Generally, at least five replicates were tested for each condition. Due to logistic problems, for some cross panel tensile testing, it was possible to test a set of three samples only.

When determining mean values, the best and the worst result was eliminated when five test results were available and the average, as well as the standard deviation was calculated from the remaining results (see chapter 9). If only three test results were available, all three results were used.

Small scale tests after artificial ageing are relatively easy to conduct and are a standard procedure for all research laboratories. Most panel producers are also equipped with the necessary equipment. This is particularly true for tests with increased temperature and uncontrolled humidity, as well as for tests with high temperature and saturated air. In both cases, the climate chambers are cheap to buy because humidity control can be omitted.
4.3.3 Results

Accurate documentation, including pictures of failure modes, can be found in appendix 1. The obtained results are discussed individually for each core material in chapter 5. Test results, other than cross panel tensile test, are evaluated in chapter 6.1.

4.4 Testing after natural ageing

A testing rig has been put up in Ingelheim near Mainz, Germany. Four sandwich panels with different core materials have been assembled. The core materials have been chosen, representing the most commonly used panel configurations. Two panels are equipped with a PUR core. One core uses carbon dioxide as a blowing agent while the other is pentane-blown. Furthermore, there is one EPS panel and one mineral wool core panel in the testing rig (see fig. 4-9a).

![Fig. 4-9a Overview of outdoor testing rig in Ingelheim near Mainz; Panels used are EPS, PUR n-pentane, PUR CO\textsubscript{2} and Stone wool (from upper left to lower right).](image)

The panels are mounted as single span beams, allowing the specimen to move without developing internal forces under temperature effects. The specimens are oriented strictly towards the south at an angle of 26.5°. This results in a perpendicular orientation towards the sun at midday on the longest day of the year at latitude 50° N. The following parameters are constantly (at 10 minute intervals) measured and recorded:
- air temperature
- global radiation
- relative humidity
- wind force and direction
- temperature at the panel surface
- deflection at mid span

Regular testing is performed on the panels. About once a month the panel is subjected to a load of approximately 2.5 kN. This load was chosen to keep the equipment, necessary for the testing, to a manageable size while, at the same time, a load around one third of the failure load was sought. The load configuration for this test is a four point bending test. A comparison with the failure load, which was determined through testing on the new panel under laboratory condition at the same support and load configuration for each panel, can be found in table 4-6.

<table>
<thead>
<tr>
<th>core-type</th>
<th>failure load [kN]</th>
<th>periodic load [kN]</th>
<th>Periodic load expressed as percentage of failure load [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>EPS</td>
<td>7.9</td>
<td>2.5</td>
<td>32</td>
</tr>
<tr>
<td>PUR Pentane</td>
<td>8.7</td>
<td>2.5</td>
<td>28</td>
</tr>
<tr>
<td>PUR CO₂</td>
<td>9.0</td>
<td>2.5</td>
<td>28</td>
</tr>
<tr>
<td>Mineral Wool</td>
<td>11.5</td>
<td>2.5</td>
<td>22</td>
</tr>
</tbody>
</table>

The deflection in each test is measured. A change in deflection under the same load can only be caused by a change in stiffness. Figure 4-10 illustrates the impact of a change in shear modulus on a simply supported sandwich beam with a thickness of 60 mm and a width of 1 meter. The face thickness for the example given is 0.5 mm and the load looked at is 2.5 kN. Assuming a shear modulus of 3.0 N/mm² for a fresh rigid plastic core material would lead to a deflection of 27.01 mm. Changing the shear modulus to 4 N/mm² while keeping all other parameters constant leads to a deflection of only 23.48 mm. If the modulus is changed to only 2.0 N/mm², the deflection would increase to 34.08 mm.
As a change in deflection could also be caused by a change in panel thickness, the dimensions of the specimen were tested before installation and after two years and 4 months of service. The results are presented in table 4-7 below.

**Table 4-7 Change in panel thickness in outdoor testing rig over time**

<table>
<thead>
<tr>
<th>type</th>
<th>Thickness 10.07.02 [mm]</th>
<th>Thickness 13.01.05 [mm]</th>
<th>change [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>EPS</td>
<td>60.1</td>
<td>59.8</td>
<td>0.5</td>
</tr>
<tr>
<td>PUR Pentane</td>
<td>40.0</td>
<td>40.4</td>
<td>1.0</td>
</tr>
<tr>
<td>PUR CO₂</td>
<td>59.2</td>
<td>59.3</td>
<td>0.2</td>
</tr>
<tr>
<td>Mineral Wool</td>
<td>79.2</td>
<td>79.6</td>
<td>0.5</td>
</tr>
</tbody>
</table>

The thickness of the panel has a quadratic influence on deflection. Based on the obtained results, this is small, in comparison to the shift induced by a change in shear modulus, and can be neglected in further discussion.

In addition, there is a smaller scale sample mounted in the same directions as the full panel. The mineral wool core specimen is equipped with two moisture sensors. These sensors constantly measure the change of humidity within the panel. For the first time, it will be possible to actually measure the moisture content of the core and the surface temperature at the same time.
4.4.1 Objectives

It was the aim of the in life testing of sandwich panels to determine time-dependent losses in stiffness under in situ ageing, which means non accelerated ageing conditions in the outdoor testing rig. Knowing that the time period of this work is limited, this part of the research is scheduled to run for an extended period. Nevertheless, if drastic changes in the beginning of the ageing would occur, this could be made visible within the time schedule of this research.

4.4.2 Results

The results from the regular load testing performed in the time period starting September 2002 and ending November 2004 are presented for each individual panel in figure 4-11 to figure 4-14. The evaluation was conducted on deflection values for a load of 2.0 kN, as not all tests reached the full 2.5 kN load level. None of the panels showed a persistent decrease in stiffness. The relative change in deflection of all panels is illustrated in figure 11-15. It was expected that testing at low air temperatures would lead to a stiffer panel, meaning that tests in winter time were expected to show a smaller deflection under the same load. Such an effect could be caused by the temperature dependency of core stiffness. In particular the plastic foam cores were expected to be sensitive to such effect. Temperature and humidity at the time of testing were, therefore, recorded separately with the testing results. The evaluation of the test and the temperature results show that such an effect was not observed.

![Graph showing deflection over time](image)

**fig. 4-11 development of deflection over time in outdoor rig under a load of 2 kN (25% of failure load) for EPS core panel**
Fig. 4-12 Development of deflection over time in outdoor rig under a load of 2 kN (23% of failure load) for PUR (Pentane blown) core panel.

Fig. 4-13 Development of deflection over time in outdoor rig under a load of 2 kN (22% of failure load) for PUR (CO₂ blown) core panel.
fig. 4-14 development of deflection over time in outdoor rig under a load of 2 kN (17% of failure load) for mineral wool core panel

fig. 4-15 development of deflection over time in outdoor testing rig under a load of 2 kN. Relative change from deflection measured in initial test

4.4.3 Commentary on results

As predicted in advance, no significant changes in stiffness were found in the presented time period. Looking at the lifetime of a sandwich panel in a real construction, the testing period is, however, very short. Since the summer of 2004 the testing intervals have, therefore, been prolonged to six months. Testing is ongoing and will proceed in the next years.
It would be possible to destroy the panels at least partly to gain information on strength parameters, such as tensile, compression and shear strength. This would, however, mean that the test on stiffness would have to be cancelled. A decision was made in favour of ongoing stiffness testing as such results are not available from any other source. Full strength testing will be performed at the end of the stiffness testing period, giving information comparable to the results presented in chapter 4.5 of this report, which is considered with the end of lifetime testing. However, the advantage will be that all relevant parameters for the specific batch of fresh panels have been determined and can be compared directly with the end of lifetime values.

The information gained on internal humidity of mineral wool core panels is presented in chapter 5.4 of this report. The data collected from temperature and wind speed, as well as global radiation is evaluated in chapter 5.2.1 of this report.

4.5 End of lifetime testing

The most realistic information on the remaining strength of a sandwich panel at any point in its lifetime can be gathered through testing. Such testing, however, requires taking a panel for preparation of test specimen from an operating building. Such a procedure would be highly cost intensive as the dismantled panel needs to be replaced and such work would probably interfere with the use of the building. Assuming a continuous decline in mechanical strength over time, suggests testing at the end of lifetime. Samples can then be taken from the panels that are taken out of service.

4.5.1 Objectives

Here, the idea is to determine the mechanical performance of panels that are at the end of their lifetime. During their service, panels are subject to durability related deterioration. The comparison of end of lifetime test results with information gathered on initial performance of panels will indicate occurring changes.

4.5.2 Implemented methods

Sandwich panels that are at the end of their life span are collected. In order to get a hold of such panels, a total of 250 letters has been sent to companies and organizations dealing with
sandwich panels. The letters were sent Europe-wide. Furthermore, advertisement was performed through internet homepages and newsletters. The idea of testing end of lifetime panel performance was presented at numerous conferences, including conferences of the European Sandwich Panel Manufacturers Association. A form, asking for all the necessary information needed on the old panels, was distributed and could be downloaded from the internet.

It is possible to collect used panels from buildings that are torn-down or extended or from sample walls on producer sites that are no longer needed. In one case, panels that had been stocked for years were made available.

After the visual inspection testing of tensile strength and modulus, compression capacity and modulus, and shear strength and modulus, as described in chapter 4.1.1 to 4.1.3 was performed. These tests are completed by determining core density.

4.5.3 Results

The amount of panels received was limited. A total of eight panels was collected and tested all together. All panels tested were steel sheet panels with a PUR core. No background information was made available for any panel. Therefore, it is not possible to compare results from juvenescent testing with end of lifetime values or to make a statement about the excitation and exposure the panel was operated in.

Commonly used PUR foams are within a limited, density-dependent performance range (Davies, 2001). In order to classify the acquired test results, they are compared to these limits.
The results from the compression tests show consistently good results. The performance in compressive strength is on average even better than expected from new panels in the same density class. The E-modulus stays well within the expected limits. A gain in compressive strength is also reported from chemical experts from other fields of application, where compression test is the standard test for determination of long term performance.
The results from the shear tests show that the obtained results are within the expected limits. This is true for both, the shear strength and the shear modulus. A significant change cannot be reported.
For the cross panel tensile strength, values rather towards the lower boundary of the expected limits were found. The samples did not show any abnormalities in failure mode. Failure happened predominantly in the core layer. No damage to the interface between core and deck layer, such as white rust zinc oxidation or corrosion from the steel face was recorded. The primer layer on the steel sheet appeared to be undamaged. The results obtained for the tensile modulus are within the expected limits.

4.5.4 Commentary on results

For all panels tested, no dramatic aberration from the expected material properties was found. It seems that the tensile strength is rather more sensitive to ageing than the other parameters tested. In particular, the E-moduli and the shear moduli seem to remain unchanged until the end of lifetime. The obtained results will be related to artificial ageing results in chapter 6.1.
5 Purpose-based accelerated ageing scenarios for sandwich panel core materials

The static performance of a load bearing member during the lifetime of a building is the probably most important factor in construction. Proper design is therefore in most cases ensured through the introduction of technical specifications such as codes and standards. These must also include the long term performance of a structure. This is in many cases done by defining accelerated ageing scenarios which help to determine the long term performance of structures. Guidance paper F (Guidance Paper F concerning CPD, 2004) requires the technical specification writer to take all foreseeable actions into account when evaluating the durability performance of a structure. Under such actions and being “subject to normal maintenance, a product shall enable a properly designed and executed works to fulfil the Essential Requirements for an economically reasonable period of time” (chapter 3.3 in guidance paper F). The durability of a construction can be verified using either performance-based methods or descriptive solutions. A combination of the two is also possible. This research concentrates on performance-based methods, meaning ageing tests determining the long term properties of important design parameters. To make such test evaluation practical, it is necessary to find accelerated ageing tests, simulating natural ageing within an acceptably short time frame. Such a process is difficult and requires fundamental knowledge of the chemical processes, leading to time dependent deterioration. This chapter presents the principles of ageing in polymeric structures and discusses the effective influences of temperature and humidity, respectively the combination of both on polymeric structures. Then it tries to pinpoint the fundamental differences in the chemical composition of the most typical sandwich panel core materials. The next step is to propose principles for accelerated ageing scenarios for each type of material. The procedures proposed in this chapter shall, however, be seen as a basis for discussion. They are not established theories, but as very little or sometimes no information on the subject is available in literature, they are meant to constitute a first step towards a quantitative evaluation process.
5.1 Ageing of synthetic material

All materials are subject to time dependent changes. Typical effects are changes in mechanical properties, chemical composition and appearance. According to Affolter these changes are caused by one of the following actions,

- auto oxidation: thermo oxidative \((T, O_2)\) and photo oxidative ageing \((h\nu, T, O_2)\)
- corrosion induced by chemicals in surrounding matrix
- biogenous ageing

An enduring or repeated loading with the previously mentioned factors leads to break down in mechanical properties. It is assumed for the purpose of this work that the changes in chemical structures lead solely to visible and physical changes. The influencing factors and the changes in properties, as identified by Affolter, are summarised in figure 5-1.

![Diagram showing factors influencing time dependent chemical changes in polymeric structures and their possible effects](image)

**fig. 5-1 factors influencing time dependent chemical changes in polymeric structures and their possible effects**
5.1.1 Biogenous ageing

For some sandwich panel constructions in special applications, biogenous ageing caused by insects, rodents, plants or micro organism such as algae, bacteria or fungi can be problematic. Such ageing is not the concern of this research. Proper construction can prevent animals entering the sandwich panel core. In addition to that, additives can be introduced to hinder the growth of bacteria and fungi.

5.1.2 Corrosion through chemicals

The changes in polymers, caused by exposure to other chemicals, are particularly important for applications where the studied material is in direct contact with other chemicals, such as oil, fat or fuels. This is particularly important if the application is a container or a pipeline. For most sandwich panel application such exposure can be excluded. This research is, therefore, concerned with panel applications lacking a distinct exposure to corrosives and oxidants. Where the attack through such chemicals can not be excluded, additional durability considerations need to be considered.

In some cases, however, it may be that the influence of such aggressive substances can barely be foreseen, not to mention quantified. Rural areas, for example, expect cleaner air than heavy industry hosting industrial areas. It is difficult to evaluate the degree of attack on a sandwich panel for each location. A possible solution is to add an appropriate durability-related safety factor, covering the variety of exposure possibilities. It would, however, be necessary to advance the research described here by means of intensive chemical studies. The procedures described in this chapter do not consider such variations.

5.1.3 Auto oxidation

Auto oxidation is defined as auto catalytic oxidation of polymers. The cycle of auto oxidation and relevant chemical reactions are shown in figure 5-2. The picture illustrates the following important steps in chemical reaction:

- In order to start the reaction, a radical (molecule with free electron) has to be formed. The formation can be a result of:
  - shear stress during production process ($r$)
  - heat (thermic energy $T$)
  - radiation ($hv$)
- Influence of redox active ions (i.e. from metals, remains of catalysts, or external metal ions from wiring or fixings)
  - Polymer chains containing hydrocarbons form aliphatic radicals (carbon molecule with unpaired electron)
  - Oxygen in its di-radical triplet form immediately reacts with the present alkyl radicals forming peroxy radicals
  - The reaction of peroxy radicals with R-H forming hydroperoxide (ROOH) is the reaction step, determining the speed of the total auto oxidation
  - After formation of hydroperoxide a chain reaction is started. Together with redox active metallic ions, the breakdown of hydroperoxide can be accelerated.

Sandwich panels are generally protected from radiation, such as direct sunlight, because of their metal faces. Also at their ends, where the foam would directly be exposed to sunlight, shading plates are obligatory. The influence of photo oxidative ageing caused by radiation can, therefore, be excluded in this research. The same is true for the influence of metal ions. Between the panel face and the core, there is always a layer of backface coating (see fig. 2-3).
separating the core from the pure metal. The influence of persistent shear stress can be neglected at this point, as it is evaluated directly through long term shear tests in sandwich design. This leaves the temperature as the most decisive factor for the formation of radicals starting polymeric deterioration.

As the formation of hydroperoxide is the speed determining reaction in this chain, changing in phenomenon, as described before, may only occur after an induction period. But after this period, changes can be drastic. For a PUR foam, where, immediately after the production process, oxygen is only present at the most outer cell structure, the diffusion process of oxygen into the foam can be assumed as the speed determining factor rather than the building of hydroperoxide. Only in the presence of oxygen, can the first step in the oxidation cycle be taken. The process of oxygen diffusion into PUR polymers is described in detail in chapter 5.5.4. Changes in properties induced by auto oxidation are not reversible.

It is possible to accelerate the auto oxidative process in a laboratory by exposing samples to elevated temperatures and testing relevant parameters thereafter. When doing so, it has to be kept in mind that due to the changed conditions, different auto oxidation reactions can be started if the chosen ageing temperature is above the temperature in the real application. An accelerated laboratory ageing then does not necessarily correlate with an in situ ageing process. Such inaccuracy, which is accepted to be a necessary assumption in many standards (i.e. prEN 253 or DIN ISO 2578), can be prevented by choosing an accelerated ageing scenario where temperatures do not exceed the panel surface temperatures found in end use conditions. For this, it is important to know what maximum temperatures need to be considered for sandwich panel structures. Ageing scenarios for important sandwich panel core materials are presented in this report.

### 5.1.4 Hydrolysis

Some thermoplastic polymers are sensitive to hydrolysis. Among these are polyurethane, as well as urea formaldehyde condensation resins, which are used as binders in mineral wools. Water is able to penetrate PUR foams, although they have a close cell structure. The absorption can be between 0.5 and 5% in weight. In principle, the same is possible for penetration of vapour. Figures for absorbency, however, are not available at the moment. In principle, ester, amide, carbonate, urethane, and ether groups in a polymer are sensitive to hydrolysis. In a hydrolysis reaction, splitting of the main polymer structure is possible. Therefore, dramatic changes in properties can be expected.
Auto oxidation and hydrolysis reactions for PUR polymers are described in 5.5.3.
Rather more important is the reaction with mineral wool cores. Mineral wools are diffusion free and humidity from the surrounding atmosphere can penetrate the sandwich panel. Particularly when together with elevated temperatures, the presence of humidity inside a mineral wool core panel attacks the binders that hold the individual wool fibres together and determine the wool’s structural behaviour. Mineral wools are, therefore, rather sensitive to a combined impact of temperature and humidity. The sandwich code prEN 14509 takes this into account by storing sandwich samples in saturated air, as described in chapter 3.4.2.2.

5.2 Factors causing degradation

For sandwich panels, there are basically two factors, which are likely to cause degradation in a sandwich panel: temperature and humidity. Other factors, such as global radiation, are only important for sandwich panels because they are the reason for highly increased temperatures on panel faces. As sandwich panels are always covered with two deck layers, the open core is protected from direct sunlight. At the top and bottom end, as well as on the edge of a building, where the core would be exposed, additional covering and protection from direct sunlight is always required. Both these important factors were monitored regularly in the outdoor testing rig. In the following, a theoretical approach for the determination of the surface temperature is checked for validity when applied to sandwich structures, which, unlike most other structures, are equipped with an insulating core directly behind the thin face. The results obtained are compared with the recordings from the outdoor rig. With the help of this approach, it is possible to determine the temperature impact on a sandwich structure depending on its orientation and location.

For the determination of humidity attacks on a sandwich core, a theoretical approach is not available. Instead, internal moisture measurements undertaken in the outdoor rig are presented.

In a next step, the most important core materials currently available are discussed in greater depth and with special focus on their durability performance. For the two most popular core materials, mineral wool and polyurethane, accelerated ageing methods are derived.
5.2.1 Temperature

The temperature on a surface is largely related to geographic position, orientation towards the sun, the temperature and movement of the air surrounding the surface, and the colour of the surface. This is also true for sandwich panels. In the outdoor testing rig, introduced in chapter 4, the temperature on all four panels was measured and recorded at ten minute intervals. The impact of the global radiation, which is the major factor, depends particularly on the surface colour. PrEN 14509 distinguishes three colour groups of sandwich panels, depending on degree of reflection ($R_G$) and anticipates maximum design temperatures ($T_1$) for these colour groups.

1. very light colours  $R_G^{14} = 75-90\%$  $T_1^{15} = 55\, ^\circ C$
2. light colours  $R_G = 40-74\%$  $T_1 = 65\, ^\circ C$
3. dark colours  $R_G = 8-39\%$  $T_1 = 80\, ^\circ C$

5.2.1.1 Determination of temperature on outer face

The development of surface temperatures for panels filled with insulating core materials, such as PU, EPS, and Mineral Wool can be described in accordance with Bark's theory (Bark et al., 1992) by

$$T_{o,max}^{eq} = T_{e,max} + \frac{\alpha_g \cdot I_{max}}{\alpha_e} = T_{e,max} + T_G \cdot max.$$  

where

- $T_o$: temperature share induced by global radiation [°C]
- $T_e$: air temperature (in shadow) [°C]
- $I_{max}$: maximum global radiation during day [W/m^2]
- $\alpha_g$: absorptivity
- $\alpha_e$: total heat transfer rate [W/(m^2K)]

with  $\alpha_e = \alpha_g + \alpha_k$

where

- $\alpha_g$: radiant heat transition rate
- $\alpha_k$: convective heat transition rate

---

$^{14}$ $R_G$ – degree of reflection relative to magnesium oxide
$^{15}$ $T_1$ – design temperature for outer face
The absorbency depends on the wave length of the hitting radiation, the angle of impact, and on the structure of the absorbing surface.

The following table 5-1 gives an overview of absorbency for different materials.

<table>
<thead>
<tr>
<th>Surface</th>
<th>max</th>
<th>av</th>
<th>min</th>
</tr>
</thead>
<tbody>
<tr>
<td>non-metal, black</td>
<td>98</td>
<td>94</td>
<td>90</td>
</tr>
<tr>
<td>dark, rugged</td>
<td>80</td>
<td>72</td>
<td>65</td>
</tr>
<tr>
<td>medium colours (red, yellow)</td>
<td>70</td>
<td>60</td>
<td>50</td>
</tr>
<tr>
<td>light colours (white)</td>
<td>50</td>
<td>40</td>
<td>30</td>
</tr>
<tr>
<td>dull metallic</td>
<td>65</td>
<td>55</td>
<td>40</td>
</tr>
<tr>
<td>polished alloy, shining</td>
<td>40</td>
<td>25</td>
<td>10</td>
</tr>
<tr>
<td>anodised alloy, light</td>
<td>25</td>
<td>20</td>
<td>10</td>
</tr>
<tr>
<td>alloy colour (varnish)</td>
<td>80</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

These figures, however, are subject to changes during the life span of a panel. Soiling on light surfaces can increase the absorbency to up to 80% on average.

When determining surface temperatures, the heat flow exchange (convective heat transition rate $\alpha_c$), which is difficult to describe in terms of mathematical equations, at the surface of the panel is of vital importance. Especially important is the wind speed which can cause a chill on the investigated face. Different literature sources, however, give different methods of taking the effect into account. The described changes in $\alpha_c$ depending on wind speed vary between 3.0 W/(m²K) and 4.2 W/(m²K) per 1.0 m/s. At the same time, the radiant heat transition coefficient ($\alpha_r$) does not show any substantial change.

The global radiation of the sun includes both, direct radiation from the sun, as well as diffuse sky radiation. Its intensity depends on the cloudiness of the atmosphere, time of year, and time of day.

As for any radiation, the global radiation also changes inversely proportional to the squared distance from the source of radiation. For the radiation intensity at the top of the atmosphere, this leads to

$$ I_0 = \frac{I'}{r^2} $$

where

$I_0$: intensity of radiation at top of atmosphere

- 85 -
\( I^* \): radiation intensity at middle of sun (which is taken as constant)
\( r \): radius of the elliptic path of the earth around the sun

The radius of the elliptic path of the earth around the sun can be described by

\[ eq. \ 5.2-3 \quad r = r_m \cdot (1 + 0.0167 \cdot \sin(\varphi - \varphi_p)) \]

where
\( \varphi_p \): phase shift of apsis (Perihelion and Aphelion)
\( \varphi \): earth rotation angle

Combining and simplifying equation 5.2-2 and equation 5.2-3 leads to

\[ eq. \ 5.2-4 \quad I_0 = I_{0m} \cdot (1 - 0.0334 \cdot \sin(\varphi - \varphi_p)) \]

where
\( I_{0m} \): \( I^*/r_m^2 \)
\( I_{0m} \): mean value of solar constant (1355 W/m²)

When penetrating the atmosphere, the global radiation is filtered according to Lambert's law for radiation filters such that

\[ eq. \ 5.2-5 \quad I_{oa} = k_A \cdot I_0 \]

The total transmission coefficient (\( k_A \)) considers the following radiation decreasing aspects:
- absorption in vapour, ozone and oxygen
- Rayleigh scatter (scatter due to molecules in pure atmosphere)
- scatter induced by aerosol

The transmission coefficient (\( k_A \)) can be connected to Link's clouding factor for natural earth atmosphere. The clouding factor indicates by how much the optical distance of direct sunbeams has to be prolonged to achieve the same weakening solely through Rayleigh scatter. The actual clouding factor changes seasonally and with the position of the considered spot.

Besides the clouding factor, the angle of incidence (\( \gamma_0 \)) is a determining factor for the hitting global radiation. The intensity of radiation hitting the ground can be described by
or together with equation 5.2-4 and equation 5.2-5

\[
eq 5.2-7 \quad I_d = k_d \cdot I_{om} \cdot (1 - 0.0334 \cdot \sin(\phi - \varphi_p)) \cdot \sin \gamma_0
\]

Assuming a panel configuration as indicated in figure 5-3 the hitting radiation can be described by

![Diagram of sandwich panels with angles](image)

**fig. 5-3** angles in outdoor testing rig for sandwich panels

\[
eq 5.2-8 \quad I_{aw} = k_d \cdot I_{om} \cdot (1 - 0.0334 \cdot \sin(\phi - \varphi_p)) \cdot \sin \gamma_0 \cdot \sin \gamma_a
\]

For a panel strictly faced southward, the maximum global radiation at noon can now be calculated by

\[
eq 5.2-9 \quad I_d = k_d \cdot I_{om} \cdot (1 - 0.0334 \cdot \sin(\phi - 12)) \cdot \sin \gamma_0 \cdot \sin(90^\circ + 23.5^\circ \cdot \sin \phi - \gamma_p) \cdot \sin(90^\circ + 23.5^\circ \cdot \sin \phi - \gamma_p + \gamma_d)
\]

where

\[
\gamma_p: \text{ angle of latitude}
\]

Here, the elevation of the sun at noon is defined as

\[
eq 5.2-10 \quad \gamma_0 = 90^\circ + \gamma_t - \gamma_p
\]
where
\[ \gamma_i: \text{ declination of sun } (\gamma_i = 23.5^\circ \cdot \sin \varphi) \]
\[ \gamma_b: \text{ angle of latitude} \]

Knowing the elevation of the sun at relevant points and times as indicated in table 5-2, some basic conclusions are drawn in accordance with Bark (Bark et al., 1992).

**Table 5-2: Elevation of Sun at Relevant Geographic Points and Distinct Times of the Year**

<table>
<thead>
<tr>
<th>Latitude</th>
<th>March 21\textsuperscript{st}</th>
<th>June 21\textsuperscript{st}</th>
<th>September 23\textsuperscript{rd}</th>
<th>December 22\textsuperscript{nd}</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Equinox (North)</td>
<td>Summer solstice</td>
<td>Equinox (South)</td>
<td>Winter solstice</td>
</tr>
<tr>
<td>North Pole</td>
<td>( \gamma_i = 0^\circ )</td>
<td>( \gamma_i = +23.5^\circ )</td>
<td>( \gamma_i = 0^\circ )</td>
<td>( \gamma_i = -23.5^\circ )</td>
</tr>
<tr>
<td>Arctic Circle</td>
<td>0</td>
<td>23.5</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Northern Tropic</td>
<td>23.5</td>
<td>47</td>
<td>23.5</td>
<td>0</td>
</tr>
<tr>
<td>Equator</td>
<td>66.5</td>
<td>90</td>
<td>66.5</td>
<td>43</td>
</tr>
<tr>
<td>Southern Tropic</td>
<td>90</td>
<td>43</td>
<td>66.5</td>
<td>90</td>
</tr>
<tr>
<td>Antarctic Circle</td>
<td>23.5</td>
<td>0</td>
<td>23.5</td>
<td>47</td>
</tr>
<tr>
<td>South Pole</td>
<td>0</td>
<td>-</td>
<td>0</td>
<td>23.5</td>
</tr>
</tbody>
</table>

The maximum global radiation for horizontal surfaces in the northern hemisphere north of the Northern Tropic is to be expected before June 21\textsuperscript{st} (\( \varphi \leq 90^\circ \)). South of the Southern Tropic, it is to be expected after December 22\textsuperscript{nd} (\( \varphi \geq 270^\circ \)). In-between the tropics the maximum global radiation occurs twice per year. Depending on the pitch of the considered surface, this can also be true for structures outside this area. For the southern hemisphere the maximum global radiation can be expected to be higher than for the northern hemisphere, as the highest elevation of the sun falls together with the closest distance between sun and earth (Perihelion). The maxima of air temperature and global radiation generally do not occur during the same period. However, it can be considered to be on the "safe side" to assume the coincidence of these two factors.

Roofs with a pitch of \( \gamma_a > 90^\circ \) must be calculated assuming \( \gamma_a = 90^\circ \), as the roof can be turned in a way, allowing perpendicular impact of radiation before the highest sun elevation is reached. Wall surfaces can be treated in the same way as roof surfaces since the radiation of the terrestrial surrounding has a strong influence, especially when looking at long wave radiation and "close to the ground" situations. This assumption, however, is conservative and on the "safe side."


5.2.1.2 Calculation example

In order to be able to calculate the maximum surface temperature, the total heat flow coefficient ($\alpha_c$) must be determined. This can be done by using figure 5-7, which gives figures for the heat flow coefficient in relation to the difference between air and surface temperatures for different facing materials.

At first, the temperature difference between element surface and surrounding air ($T_{\text{air}}$) is estimated or determined through testing. The corresponding value for $\alpha_c$ is then taken from figure 5-7. By making use of equation 5.2-1 and knowing $\alpha_c$, it is now possible to calculate $T_0$, where $T_{\text{air}} \approx T_G$ must be fulfilled. When looking at short term temperature loads with duration of less than 10 minutes, the wind chill factor should be neglected. For longer temperature loads, a wind speed of 1 m/s can be assumed, elevating the total heat flow by 3.0 to 4.2 W/m²K.

In order to determine the temperature loads, it is important to know the relevant climatic factors for a particular region. For the given problem, these are the average of the monthly maximum temperature and the annual development of maximum global radiation. Both factors are generally provided by local meteorological services. For the purpose of this research, these factors were also determined for the outdoor testing rig in Ingelheim. Typical annual developments of these factors for different climatic regions based on literature (Barl et al., 1992) are illustrated in figure 5-6 and figure 5-5.

The five regions that were examined are:

- Addis Abeba (equatorial region)
- Damascus (arid region)
- Berlin (temperate region of Central Europe)
- St. Petersburg (cold region)

and additionally, based on the gathered data,

- Ingelheim (Central Europe, outdoor testing rig)

Due to lack of long term information, the data for Ingelheim is based on the years 2002 and 2003.
The constant recording of global radiation on a horizontal plane ($I_0$), the surface temperature on the four sandwich panels, and the surrounding air temperature allows the calculation of the heat flow curve for the tested panels. For this calculation, it is assumed that for the panels, equipped with an organic black coating, the total absorbency ($\alpha_t$) is 95%. For the mineral wool core panel coated in dark red, the absorbency is assumed to be 85%. In order to calculate the intensity of radiation hitting the panel pitched at an angle of 26.5°, it is necessary to know the elevation of the sun at noon for the area of the test rig.

By making use of equation 5.2-1 and the data gathered in the testing rig, it is now possible to determine the total heat transfer rate. The result for the individual panels in comparison with...
literature data for $\alpha_e$ is shown in figure 5-7. The found values for all panels, independent from their core material, gather around the theoretical line for colour coated surfaces. This indicates that the surface temperature development is independent from the panel core and largely depends on the structure of the panel surface. The data chosen from the testing rig is based on data gathered on clear days with low winds, minimizing the cooling effect of the wind and allowing the panel to reach peak temperatures. As zero wind is never reached, at least in average during a 10 minute testing period in an exposed surrounding, the influence on the heat transfer rate was assumed to be 3.5 W/m²K per 1 m/s wind speed.

Fig. 5-7 total heat flow coefficient; literature data and test results

For the five locations given here, it is now possible to estimate the temperature load for different panel surface types. For the calculation, a concurrence of maximum radiation and maximum air temperature is assumed.
Table 5-3 shows the calculated temperatures at outer faces for sandwich panels in different locations. The most unfavourable results were obtained for aged and soiled, galvanized surfaces. Here, the surface temperature of 80°C assumed in prEN 14509 for design procedures is exceeded both in long- and short-term intervals. The same is true for faces with dark (black) finishes. The classification of panels into three groups (prEN 14509) also shows deficits when looking at peak temperatures.

For the testing rig in Ingelheim, the observed peak panel temperature in the evaluated time period between 2002 and 2003 was 87 °C.

### 5.2.1.3 Synopsis

Table 5-3 shows the calculated temperatures at outer faces for sandwich panels in different locations. The most unfavourable results were obtained for aged and soiled, galvanized surfaces. Here, the surface temperature of 80°C assumed in prEN 14509 for design procedures is exceeded both in long- and short-term intervals. The same is true for faces with dark (black) finishes. The classification of panels into three groups (prEN 14509) also shows deficits when looking at peak temperatures.

Table 5-4 comparison of expected temperatures for colour groups according to prEN 14509 with measured temperatures in Ingelheim and theoretical values for Berlin

<table>
<thead>
<tr>
<th></th>
<th>( R_g ) reflectivity</th>
<th>( T_1 ) (prEN 14 509) design temperature</th>
<th>( T_{a\text{max}} ) (Ingelheim) measured values</th>
<th>( T_{a\text{max}} ) (Berlin) theoretical temp.</th>
</tr>
</thead>
<tbody>
<tr>
<td>dark colours</td>
<td>8 - 39</td>
<td>80</td>
<td>85 - 94</td>
<td>75 - 83</td>
</tr>
<tr>
<td>light colours</td>
<td>40 - 74</td>
<td>65</td>
<td>66 - 84</td>
<td>58 - 74</td>
</tr>
<tr>
<td>very light colours</td>
<td>75 - 90</td>
<td>55</td>
<td>42 - 65</td>
<td>38 - 57</td>
</tr>
</tbody>
</table>

The safety deficit in temperature load observed varies between 15 % and 22 % based on the Ingelheim data and 4 % to 12 % for the Berlin literature data. On the other hand there is a
large reserve for some colours that are at the lower end of their colour group concerning their absorption capacity. The same is true when looking at northern regions, where solar radiation stays far lower than in the southern part of Europe. This could be improved by introducing more accurate design methods, based on the presented formulas and the accurate climate recordings (monthly average of maximum solar radiation and monthly average of maximum temperature).

Furthermore, it has to be considered that material properties may be influenced by elevated temperatures. This is particularly true for foam core panels. Additional precaution should be taken when temperatures exceed 80°C. Additional steps like shading and banning of dark colours must be taken for regions with likeliness of high air temperatures or high solar radiation.

The temperatures observed for long-term periods vary between 75 to 85% of the values determined for short-time periods. This supports the assumption that, in combination of temperature and wind load, the temperature load can be factored by 0.8. Increased wind speeds inevitably lead to rapid temperature drops on panel faces. This is especially true because in table 5-3 the assumed wind speed for long term temperatures is only 1 m/s, which corresponds to a wind pressure of not more than 0.62 N/m² on a vertical plane.

When looking at test temperatures for durability testing on sandwich panels, one has to take into consideration that even for moderate Central European areas like Berlin and Ingelheim long term temperatures of 80°C can be reached. When looking at southern Europe, expected temperatures are closer to 90°C. Exposing small scale samples in artificial climate chambers to temperatures of 90°C can be considered as reasonable, as these temperatures are observed also on in-life panels. The deterioration reactions activated in a climate cabinet at 90°C, as proposed for dark colours in prEN 14509, are likely to occur in an on site panel also.

### 5.2.2 Humidity and moisture

Besides temperature, humidity and moisture are decisive factors for the ageing of the sandwich panel core material. Because of this, mineral wool cores, as well as EPS and XPS cores are tested according to the DUR 2 test as described in 3.4.2.2. It may be argued that moisture does not penetrate a sandwich panel as jointed panels form diffusion tight walls. This may be true for moisture attacks from the inside of the building, but, in any case, sandwich panels are open at their cut ends and the moisture of the surrounding air can penetrate the panel. Humidity development in a sandwich panel is difficult to predict. The air tightness of a joint, together with the use of the interior of the building has a considerable
influence on the internal panel moisture. The same is true for the location of the building. Extensive botanical growth around the building may lead to damp conditions. These conditions may even vary with different sections of a building. A first approach to the determination of internal sandwich panel climates on a free standing sandwich sample was taken in this research. For humidity observations in the outdoor testing rig, a small sandwich panel sample with cut edges and a dimension of 500 x 500 x 80 mm was equipped with two moisture sensors.

![Fig. 5-8 Mineral wool core sandwich panel element equipped with two moisture sensors for continuous recording of internal moisture contents (top view left; bottom view with sensors right)](image)

The sample was pitched at an angle of 26.5° and strictly oriented south. This setup cannot be seen as a worst case scenario for humidity attack, but allows comparison with the neighbouring full panel, where the surface temperature was monitored. Again values are recorded in 10 minute intervals. To shield the panel partially from the surrounding air and to simulate a panel application situation, the sample edges are sealed with strong water resistant duct tape. Additional silicone sealing at the area of contact between upper face and tape hinders rain water from penetrating the sample. The tape is detached from the lower face of the sample, leaving a gap of approximately 2 mm that allows air flow between the panel interior and the surrounding atmosphere. Such measurement of direct and continuous determination has been conducted in this research for the first time. Only with advanced humidity sensors and in combination with constant data logging, it is possible to evaluate internal panel climates consistently. Two Lufft Opus 10 data loggers were adapted for this special measurement task. One logger was equipped with internal moisture and temperature sensors, recording air temperature and relative humidity outside the panel. The other was hooked up to two sensors placed inside the mineral wool panel. The sensors penetrated the sample through the lower face. The penetration area and the lower part of the sensor itself
were sealed, hindering air to penetrate the panel through the locally damaged face. One humidity sensor was placed in the centre of the panel while the other was placed 100 mm from the edge of the sample. The sensors apply a capacitive measurement principle, allowing a measuring range between 0 and 100% relative humidity. The accuracy throughout the measuring range is ±2% relative humidity at a resolution of 0.5%. The sensors are covered with porous plastic, allowing free air convection to the sensing element. The sensors are of cylindrical shape with a length of 50 mm and a diameter of 6 mm (see fig. 5-9).

![Humidity sensor](image)

**fig. 5-9 humidity sensor before insertion in MW panel; length 50 mm, diameter 6 mm**

Some problems with the first generation of sensors were experienced. Condensation inside the panel damaged the circuit board of the sensing element so that a second generation sensors with additional protection of the circuit board replaced the initial sensors.

On a typical day, it is observed that the humidity inside the panel increases according to the surrounding humidity but with a considerable time gap. If the surrounding humidity decreases, the internal humidity again reacts with a gap in time.

![Humidity and temperature graph](image)

**fig. 5-10 development of surface temperature and relative humidity, both inside and outside a mineral wool core panel on a typical day in autumn (end of October 2002)**
The effect is illustrated in figure 5-10. An increase in temperature (1) on the panel face has a direct impact on the temperature dependent relative humidity. This is true for both, the surrounding humidity, as well as the humidity inside the panel. As soon as the temperature on the face drops again (2), the relative humidity raises. The effect is also observed inside the panel but with a delay in time. With the recorded data, it is now possible to determine the internal panel climate over a complete year. All occurring temperature and humidity combinations, as well as their length of time are available for evaluation. This provides the base for determination of an accelerated ageing scenario, simulating the exact influence of temperature and humidity combinations for accelerated ageing. Such ageing scenario is presented and discussed in chapter 5.4 of this report where the test data from a full year of recording is analysed.

5.3 EPS/XPS cores

Expanded (EPS) and in particular extruded (XPS) polystyrene based foam core materials are playing a less important part in today’s sandwich panel markets. This is particularly true for the European market but this is also true worldwide, but with a certain time lag. The main reason for this is probably the bad fire performance of such panels. Nevertheless, EPS panels were extremely popular in the recent past as the material is cheap and easy to produce. This chapter gives background information on styrene polymers and explains why durability issues are less critical than in most other core materials, in particular PUR, as the chemical structure of styrene polymers is well understood and from a chemical point of view comparatively easy structured.

5.3.1 Introduction

Polystyrenes were developed in parallel in the US and in Germany in the early 50’s. It was Dr. Stastny from BASF who introduced the new product at the 1952 Duesseldorf plastic trade fair, the same year the first patent dealing with polystyrene was published. The patent described the thermal polymerisation of styrene in the presence of pentane, resulting in absorption of the hydrocarbon. The polymer, when heated, released the low boiling pentane ($C_5H_{12}$) and formed low density foam; expanded polystyrene (EPS). Extruded polystyrene (XPS), where the blowing agent is added during the extrusion of a polystyrene mould, was
developed in the same decade by Dow and Koppers, which is today known as ARCO, in the United States (van Dorp, 1993 and 1996).

Ever since, the world demand of polystyrene has grown rapidly. Polystyrene has a wide field of applications, ranging from the food industry to the construction industry. Polystyrene products are in widespread use for containers, such as single use coffee cups, packaging for technical devices, meat-, fish-, fruit- and vegetable-boxes, as well as parts of packaging for any fragile product, such as glasses and ceramics. The properties influencing its use in these areas are the combination of lightweight and high stability, as well as superb shock absorption and good thermal insulation values. Altogether there is a world wide annual demand of 1,500 thousand tons of EPS/XPS (van Dorp, 1993).

The construction industry makes wide use of polystyrene, exploiting its good thermal insulation values and general mechanical properties. It is used as an external or sometimes internal thermal insulation layer for concrete and brick buildings. The thickness of these layers has rapidly increased over the last decade. Today highly energy efficient “passive” houses are common. The latest increase in legal demands towards the insulation of buildings in Germany came into power at the beginning of 2002. Cellular bricks, such as “Porotone” are produced using prefoamed PS as an additive. Drainage boards, which are known as “Sickerplatten” in Germany, are a common application. In France EPS-gypsum sandwich panel products, known as “doublage,” have a major market share. Structural floor elements from EPS are typically found in the Netherlands (“broodjes”) and in France (“bourdis”). Pre-manufactured slightly sloped roof insulation systems for warm deck flat roofs, so called “Klappbahnen,” which can be pre-fashioned with a layer of bituminous coating are used for new, as well as renovated roofs (van Dorp, 1996).

Since the early 1970’s EPS blocks have been used as a foundation for roads to improve the load capacity of the supporting soil (“geofoam”). This technique was first developed in Norway but is nowadays used all over the world. Instead of excavating and replacing soil that shows insufficient load bearing capability, such as soft clay or silt, the incoming loads are spread through the polystyrene blocks. Due to their low density, these blocks do not impose any significant additional load and, therefore, minimize the settlement of the foundation soil. When looking at the durability of polystyrene, researches, covering this type of road building, indicate unproblematic behaviour. Blocks covered with soil without additional protection show no problems towards mechanical strength properties.
Usually, EPS beads are produced and then shipped to the manufacturer of, for example, sandwich panels. Depending on the field of application, different properties are desired. Therefore bead sizes, the amount of blowing agent, and other additives vary. The polymerisation generally takes place in a suspension of water and styrene monomer with addition of pentane, which is the most common blowing agent, during the radical polymerisation. During the polymerisation process, the reactor, which varies in size from 20 to 100m³, is kept at a controlled temperature and pressure. Organic peroxides are used to start the polymerisation process. Controlling the radical concentration allows controlling the speed of the polymerisation and, therefore, influencing the size and weight of the produced beads. Suspension stabilisers, stirrers, and reactor geometry are further tools to control the outcome of the process. When the beads have reached a certain dimension and weight, they start to “sink” inside the reactor. At this point the blowing agent is distributed homogeneously and the reaction comes to an end. The reactor is then brought to ambient temperature and pressure, to be discharged. In modern European reactors, the level of residual styrene in EPS beads is below 0.1 % weight. Depending on customer demands, some chemical modifications in the polymerisation are made. For the construction industry fire retardants like brominated cyclic hydrocarbons and special peroxides are added to increase the fire performance of EPS. Further additives, known as nucleating agents, are used to determine the morphology of the beads and subsequently the geometry of the final foam. After the polymerisation, the beads are dried and sieved. Different fractions of bead sizes are used for different applications. Either before or after sieving, the beads are coated with special
coating systems. The coating optimises the later conversion processes. It also reduces the occurrence of static electricity. Depending on the bead size and end application requirements, the coating varies. This is one of the producer specific secrets of EPS chemistry. After the coating, the EPS beads are delivered to the foam producer.

**5.3.2 Basics of EPS chemistry**

The chemistry of the polystyrene polymerisation is well described through basic reactions. Benzene and Ethylene react under the presence of AlCl₃ (Aluminium-tri-Chloride), forming Ethylbenzene.

![Equation](image)

**fig. 5-12 Benzene and Ethylene react under the presence of a catalyst (AlCl₃) forming Ethylbenzene**

Ethylbenzene then reacts in a catalytic dehydration at the presence of either ferrous- or chrome- oxide and forms styrene. The reaction is endothermic and temperatures of around 600°C need to be provided.

![Equation](image)

**fig. 5-13 Ethylbenzene with catalytic metal oxides forms styrene in an endothermic reaction**

The polymerisation of Styrene forming Polystyrene (PS) is an exothermal reaction. The reaction is initiated either through temperature, light (photochemical initiation), radicals, cation or anions. When oxygen is kept out, the reaction forms a rigid, glassy polymer. At the presence of oxygen the polymer’s colour changes to brownish.
5.3.3 Durability of EPS in Sandwich Panels

Nowadays the amount of sandwich panels with an EPS core sold in Europe is marginal when compared with mineral wool cores or polyurethane cores. This is basically because of the poor fire performance of EPS cores. Melting occurs at temperatures of about 80 °C; this makes EPS inapplicable in panels with dark coloured faces, as core temperatures for such panels can rise well above this level (see chapter 5.2.1.1).

The simple polymerisation reaction and the uniformity of chemical bindings make the bond enthalpy for EPS polymers predictable (350°C). EPS tends to melt before polymerization links break. The influence of temperature on an EPS panel is, therefore, not problematic with regards to durability but rather with regards to loss of dimension stability. When attempting accelerated ageing of EPS samples at 90°C and low humidity, melting deformation can be observed (see fig. 5-15).
The melting of EPS cores cannot be considered as a durability problem. It is rather important to respect that EPS cores are generally not suitable for panels with dark surfaces where temperatures are likely to exceed 80°C.

Other applications also suggest that long term performance of EPS with regards to humidity is not problematic if temperatures stay low. EPS blocks are, for example, used in road construction to build road dams, spreading loads in areas where the ground is not able to carry the road by itself. This makes extensive excavation and soil replacement unnecessary. Such blocks are protected from direct sunlight and high temperatures through coverage with a layer of soil. These structures maintain their load bearing capacity for a long time (Duškov, 1998), even under very damp conditions.

The cross panel tensile tests on EPS core samples undertaken in this research support these observations. The results are summarized in figure 5-16.
Temperatures of 90°C melt the EPS core, which leads to a complete loss of tensile strength when combined with humidity. With high temperatures and dry air, the effects is less severe but clearly visible. Lower temperatures, even when combined with high humidity, show a lot smaller decrease in tensile strength. The relatively high loss in strength after 28 days of ageing at 65°C and 100 % RH comes together with a high standard deviation of 0.018, which makes the result a little less reliable than the other results. The connection between melting of the core and loss in cross panel tensile strength is also clearly visible from the failure mode obtained in the tests. The results which are documented in chapter 9 of this report show clearly that, when the first set of specimen was tested after seven days of exposure, melting has already occurred. The process increased with prolonged exposure until sample faces detached completely prior to testing.

It has to be kept in mind that deterioration can happen not only in the PS core itself but also in the bonding area between core and face. In PS sandwich structures the bond between face and core is always established with the help of glue. In most cases, Polyurethane-based glues are used. Throughout the lifetime of a sandwich panel, the link between face and core should remain non-critical. This is particularly true for panels where an adhesive layer is formed with the help of glues. Such glues can be chosen, in a way ensuring adequate performance throughout the lifetime of a panel. The wedge test as described in chapter 3.4.2.4 ensures such
a performance. The test is so severe in combining fatigue strength loading with complete immersion into hot water that a passed wedge test ensures a sufficient bond between, face and core.

5.4 Mineral Wool cores

Structural mineral wool cannot be compared with the mineral wool used for insulation purposes although it shares the same production process. Structural woods are of significantly higher quality. The loss of mechanical strength properties observed in mineral wool core panels in the past has initiated the durability considerations for sandwich structures. The ageing process is a result of the deterioration of binder polymers. This chapter tries to find an accelerated ageing scenario for mineral wool sandwich panel by combining test result-based theories with, for the first time recorded, internal panel climates of a full year of natural exposure. Only with the combination of the two pieces of information is it possible to determine if an artificial ageing scenario is sufficiently accurate in simulating real time ageing.

5.4.1 Introduction to mineral wools

Mineral wool core is the generic term for mainly two kinds of wool materials which differ in raw material. Depending on the raw material used, it is important to distinguish between mineral stone wool and mineral glass wool. While the two products are more or less produced in the same way, they consist of different raw materials. Mineral stone wool uses melted natural stone while glass wool consists of melted glass. The main difference is the melting temperature of the two materials. While glass melts at about 700°C, the melting point for stone is roughly 1300°C. Currently, there are very few glass wool cored sandwich panels on the market. This research, therefore, concentrates on the far more common stone or rock wool panels.

Natural lime stone, the raw material, is melted and droplets of the molten mass are blown on a rotating band. This forms fibres between 3 and 8 μm thickness and a length of several millimetres. The main orientation of the fibres is parallel to the direction of the blowing air stream. In order to get the fibres connected to each other, a binder is sprayed onto the substrate, the so-called primary layer of fibres. Several of these primary layers are now stacked and cured in an oven at a temperature between 200 and 250°C. The amount of layers
determines the thickness of the produced wool slab. In the oven the binder hardens and establishes connections between individual fibres (see fig. 5-17). Because of this production process, the material properties perpendicular to the primary layers are very low. The bond between these layers is little. Parallel to the primary layer, very good structural performance can be obtained. For usage in a structural sandwich panel, mineral wool slabs are, therefore, cut into lamellas and turned 90 degrees. This results in the gross amount of fibres in the wool core running perpendicular from face to face.

fig. 5-17 microscopic photography of mineral wool fibres with droplet of hardened binder connecting individual fibres. Scale: 1mm ≈ 2μm

5.4.2 Chemistry of MW binders

The amount and type of binder sprayed on during the production process is one of the principal factors in determining the structural strength of the mineral wool. This is also true with regards to durability performance. Typically, a mixture of phenolic and urea-formaldehyde resins is used. The ratio of the mixture varies from producer to producer. For economic reasons, producers try to change the ratio in favour of the urea-formaldehyde resin (UF-resin), as this is the cheaper product. Cured UF-resin is not completely stable to hydrolysis. Here, the reaction between urea and formaldehyde is partly inverted under the attack of moisture and water. The reaction is more rapid at elevated temperatures (Dunky, Niemz 2002). A certain amount of formaldehyde evolves from this reaction. The amount of produced formaldehyde is, in literature, used as an indicator for the speed and progress of the hydrolysis. When the reaction progresses, primary and secondary polymeric structure is
destroyed. This inescapably leads to a reduction in mechanical strength of the bond between individual fibres. It can, therefore, be assumed that the process influences all mechanical properties of the mineral wool. This includes tensile strength, compressive strength, and shear strength. The associated elastic moduli are also affected. Dunky and Niemz (2002) report that the fundamental factors affecting the hydrolysis and durability are:

- temperature
- humidity
- pH-value
- curing state of resin

The hydrolysis reaction itself is described in literature as rather complex. It is not possible to identify a single reaction scheme responsible for the degradation. Influencing factors, such as interconnectedness of the polymer, occurrence of individual, sensitive chemical bindings, mole ratio between urea and formaldehyde, and curing conditions are of great importance. Under similar ageing conditions different strength losses for individual resins are described in literature.

![Graph showing time dependent development of formaldehyde concentration in ageing mineral wool. The reaction speed is temperature dependent. (taken from Dunky and Niemz, 2002)](image)

**5.4.3 Results from cross panel tensile tests**

Knowing that both temperature and humidity affect the ageing of mineral wool cores in sandwich panels, it is now desirable to know the influence they both have on the mechanical performance of such a panel. The effect is studied by exposing mineral wool samples to different combinations of temperature and humidity for defined time intervals. Here, once more, the cross panel tensile strength is considered as a good indicator for changes in
mechanical properties. An overview of the outcome found in this research is illustrated in figure 5-19.

![Graph showing the results from cross panel tensile strength on aged mineral stone wool core samples. Ageing effects depend on the combination of temperature and humidity.](image)

**fig. 5-19** Results from cross panel tensile strength on aged mineral stone wool core samples. Ageing effects depend on the combination of temperature and humidity.

The loss in cross panel tensile strength under a variety of climates has been studied in detail by Reentilä (2003) and during the ASPAN research. When comparing the results obtained in this research (see fig. 5-19) with results from Reentilä (2003) and the ASPAN research some differences are found. It is expected that increased humidity and increased temperature lead to a faster loss in strength. This can be found in the ASPAN results (see fig. 5-20) and is also reported by Reentilä.
The reason for this is that cross panel tensile tests on mineral wool core samples are generally more problematic than those on other core materials. Mineral wool is a very inhomogeneous material. The scatter in results is often rather large. Such is also true for the results presented here. The results for the 50°C and 80% relative humidity combination after exposure of seven days vary between 0.129 and 0.196 N/mm². It would have been reasonable to enlarge the size of the tested samples as larger cross sections minimize the effects of local discontinuities in the wool. At the beginning of this research, when sampling was undertaken, it was, however, unclear if the geometry of a sample would have an influence on the accelerated ageing process. Therefore, equal geometries were chosen for all accelerated ageing tests. In order to reduce the number of tests conducted during this research, the number of specimen in some series (series: equal exposure time to a particular climate) was reduced to three samples (see table 5-5 or for more detailed information refer to chapter 9).
It is particularly discontenting that the results obtained for the 50°C / 80% RH are lower than those for the 50°C / 90% RH combination, but here again the obtained deviations vary considerably. The interpretation of these results is problematic. Due to the problems obtained in the tests conducted in this research further considerations are based on the results presented by Reentilä (2003). Combining results from all three sources and knowing the development of formaldehyde concentration as presented by Dunky and Niemz, a model describing the ageing of a mineral wool core can be found. Reentilä in his modeling of time dependent loss in cross panel tensile strength for individual climates assumes a development that can be described sufficiently correct through a power law model. Such development corresponds to the principles of chemical degradation presented in figure 5-18. Reentilä introduces an ageing rate coefficient and presents two possible models. An exponential model where

\[ n_{T,RH} = e^{(\frac{M}{T} - N \cdot RH - C)} \]

where
- \( n_{T,RH} \): ageing rate coefficient dependent on temperature and relative humidity
- \( M \): core specific material constant (temperature factor)
- \( T \): temperature in the environment
- \( N \): core specific material constant (humidity factor)
- \( RH \): relative humidity in the environment
- \( C \): core specific material constant

and a linear model where

\[ n_{(T,RH)} = D \cdot T + E \cdot RH + F \]

\[^{16}\text{rms}\] - root mean square error, see also chapter 9
where

\[ n'(T, RH) = \text{ageing rate coefficient dependent from temperature and relative humidity} \]
\[ D = \text{core specific material constant (temperature factor)} \]
\[ N = \text{core specific material constant (humidity factor)} \]
\[ F = \text{core specific material constant} \]

In both models the material constants are derived from testing. This means that they are, in principle, valid for one specific panel type only. The fact that they are derived from cross panel tensile test is of minor importance. The test just generally needs to indicate the loss of fibre links in the material. Similar results could be expected from, for example, shear tests. The cross panel tensile strength, however, has the advantage that it takes the glue bonding between face and core into account. The obtained test results, therefore, not only include the loss in performance of the core itself, but the change in the whole cross section. Further consideration of the gluing area is, in principle, not necessary in this model.

![Graphical presentation of the two models](image)

**Fig. 5-21** comparison of exponential (left) and linear (right) model for ageing rate coefficients \( n \) and \( n' \) as presented by Reentili (2003)

The two models are graphically presented in figure 5-21. It is important to note that the two ageing rate coefficients \( n \) and \( n' \) are not directly comparable. They only indicate relative ageing effects of a certain climate in comparison with another climate. There are, however, big differences between the two models. Mathematically, the linear model changes its sign of \( n' \) from plus to minus at a certain temperature/humidity combination. This mathematically suggests that below a certain temperature and humidity a curing effect occurs. Such an effect is not reported from chemistry and not obtained from testing. Values for \( n' \) below this border are, therefore, set to zero. In the exponential model the ageing rate coefficient \( n \) never reaches zero. A typical value for a 0°C and 0% RH combination is \( n = 2 \times 10^{-3} \). Comparing this to a
typical result for a temperature of 100°C in combination with saturated air (100% RH), where \( n = 1.07 \), suggests that ageing proceeds approximately 0.5 million times faster than in cold and dry condition. This difference in models becomes important when looking at real climates in mineral wool sandwich structures. In chapter 5.2.2 a constant temperature and humidity observation inside a sandwich panel in a real life scenario has been described. Figure 5-22 shows the frequency of occurrence of all possible climates as measured in a one year period starting 01.09.2003 and ending 01.09.2004. A total amount of 92% of all theoretically gathered data could be used for the evaluation. It becomes obvious that high humidity only very rarely occurs together with high temperature.

![Diagram](image)

**fig. 5-22** frequency of climatic conditions inside a mineral wool core panel. Data was gathered in Ingelheim testing rig between 01.09.2003 and 01.09.2004. The magnified part shows data accounted for in linear model only.

Figure 5-17 magnifies the part of data beyond the border where ageing occurs in the linear model. The border lines are based on results obtained by Reentilä (2003). Clearly the most frequent occurring climates are not taken into consideration in the linear model. This includes climate combinations such as 70°C and 60% humidity. The results from the ASPA project
show, however, that deterioration in such climate combination can be significant. Losses of almost 40% of strength are reported. The exponential model on the other hand accounts for all climates.

Knowing the function for the ageing rate coefficient of a certain mineral wool and knowing the internal climate of a mineral wool panel, it is now possible, for the first time, to combine the information and determine an equivalent artificial ageing scenario for a climate cabinet or a tropic box. In order to do so, an artificial ageing temperature and humidity combination must be chosen first. This can, for example, be 70°C and 100% RH in a tropic box as suggested in prEN 14 509 for the DUR 2 test. The value for the ageing rate coefficient is then set to 1 at that particular climate. All other members of the matrix can thus be transformed by multiplication, giving a relative ageing rate ($n_{rel}$) for a certain mineral wool in any possible climate in relation to the chosen ageing condition. Based on the results presented by Reentila (2003), the matrix from the exponential model for the 70°C / 100% RH combination appears as presented in figure 5-23.

![Fig. 5-23 Relative ageing rate coefficient for a climate combination of 70°C and 100% RH. Matrix is set up with 5°C increments for temperature and 5% increments for relative humidity.](image)

The data presented implies a temperature factor of $M = -5927.23$ and a humidity factor of $N = 0.0498$ together with a constant of $C = 10.97$, factors derived from small scale cross panel tensile testing.

It is now possible to multiply this matrix with the climate matrix presented in figure 5-22. The result is a matrix showing how much time a sample needs to be stored at the chosen artificial ageing climate to experience the same deterioration as in any other particular climate.
combination. For the chosen ageing climate the relative ageing coefficient $n_{rel} = 1$. This means that the in situ occurrence of the climate and the time figure in that particular point of the matrix are equal.

The sum over all matrix components then tells how long a sample needs to be stored under the chosen condition to experience the same climatic ageing impact as in the Ingelheim outdoor testing rig in a one year period. For the results obtained in the Ingelheim outdoor testing rig and in combination with the results found by Reentila (2003), the following values are found:

<table>
<thead>
<tr>
<th>Model</th>
<th>Climate</th>
<th>Required testing time to simulate 1 year</th>
<th>Required testing time to simulate 25 years</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Temperature</td>
<td>[°C]</td>
<td>rel. Humidity</td>
</tr>
<tr>
<td>linear</td>
<td>70</td>
<td>100</td>
<td></td>
</tr>
<tr>
<td>exponential</td>
<td>70</td>
<td>100</td>
<td></td>
</tr>
<tr>
<td>exponential</td>
<td>90</td>
<td>100</td>
<td></td>
</tr>
</tbody>
</table>

For a variety of other climates and under implementation of the exponential model, the necessary artificial ageing time to simulate a one year period of natural ageing is illustrated in the left chart in figure 5-24. Here, a less severe artificial climate requires a longer exposure time. Thus, the angle formed between the natural time to be simulated and the time needed for the simulation is given by:

$$\alpha_{\text{temperature, humidity}} = \arctan \left( \frac{\text{time needed for simulation}}{\text{time to be simulated}} \right)$$

The evaluation has been carried out for a variety of possible climate combinations and the corresponding angles were calculated. The obtained results are illustrated in figure 5-24.
fig. 5-24 illustration of time necessary to simulate one year of ageing at different climates

fig. 5-24a characteristic curve combining temperature and humidity with angle found in fig. 5-24

The found curves now allow choosing a certain temperature and humidity combination and read the required testing time, needed to simulate a single year of natural ageing, from the chart. If for example a climate of 40°C and 60% RH is chosen, the corresponding reading from the chart is 36.0°. This means that the required testing time is determined by:
required testing time = \tan(\text{reading}) \cdot 365

or, for our example:

\[
\text{required testing time} = \tan(36^\circ) \cdot 365 = 0.726 \cdot 365 \text{days} = 265 \text{days}
\]

### 5.4.4 Discussion of results

Two models describing ageing scenarios in sandwich structures with mineral wool cores were presented. One model follows a linear mathematical approach while the other is based on an exponential equation. The exponential model takes all possible climate configurations into consideration. Both models implement results from small scale cross panel tensile testing. This hypothesises that changes in cross panel tensile strength indicate the ageing progress in a sandwich panel. Unfortunately, the loss in tensile strength after ageing does not always follow a mathematically describable curve as indicated in figure 5-18. This leads to a relatively rough assumption for the material dependent coefficients in equation 5.4-1. Combining this with the results from a single year of internal moisture and temperature monitoring on a single panel in a single location, this can only give hints to an expedient ageing test for sandwich structures with a mineral wool core. The results presented in table 5-6, however, suggest that an ageing scenario as presented in prEN 14 509, Annex B3, which lasts for a maximum period of 56 days at a temperature / humidity combination of 65°C and 100 % RH, cannot be considered to be on the “safe side.”

Based on the developed model, it is now possible to calculate how the artificial ageing relates to natural ageing. In the following example, such calculation is executed for the climates chosen for the cross panel tensile test in the ASPAN research. The result is a time axis modelled for each climate and showing the corresponding time lapse in natural speed. For the different climates, the relationship between artificial ageing and natural ageing is presented in table 5-7.
Table 5-7: Relation between artificial and natural ageing time for small scale tensile tests

<table>
<thead>
<tr>
<th>Climate</th>
<th>Required testing time to simulate 1 year of natural ageing</th>
<th>90 days in climate chamber corresponds to x years natural ageing</th>
</tr>
</thead>
<tbody>
<tr>
<td>[°C]</td>
<td>[d]</td>
<td>[years]</td>
</tr>
<tr>
<td>90</td>
<td>15</td>
<td>184.5</td>
</tr>
<tr>
<td>70</td>
<td>60</td>
<td>50.8</td>
</tr>
<tr>
<td>50</td>
<td>98</td>
<td>20.2</td>
</tr>
<tr>
<td>50</td>
<td>80</td>
<td>54.7</td>
</tr>
<tr>
<td>65</td>
<td>100</td>
<td>8.9</td>
</tr>
</tbody>
</table>

Applying these results to figure 5-20 and omitting the result for 90 days of ageing at 50°C and 98 % RH, which can be seen as an outlier, leads to figure 5-25.

Fig. 5-25: Expected development of cross panel tensile strength under natural ageing conditions based on results obtained from different artificial ageing scenarios.

The consistency of the obtained results for the initial part of the curves is very good apart from the results for the 50°C, 80 % humidity combination. These results are questionable anyway as they suggest an increase in performance. The 65°C and 100 % humidity combination simulates the longest natural ageing period. All other curves swivel in on the gradient of that curve quickly. A constant decline in strength is observed. The slope decreases over time and it seems that a maximum is reached at around 40 % of the initial strength. Such behaviour is backed up with the gained information on composition of mineral wool binders.
The UF-resin deteriorates through hydrolysis reaction, but the phenolic fraction remains unaffected and assures a minimum of enduring strength. The results have to be considered with care, as they are, a mixture of observations obtained by Reentilä (2003) and results from the ASPAN research. In particular, the core specific material constants for temperature and humidity effects were adopted from Reentilä’s research.

Recapitulating, it can be said that an ageing model for sandwich panels with a mineral wool core has been found. The model is based on a theory presented by Reentilä (2003) which employs a variety of results from cross panel tensile tests on artificially aged samples, but is, for the first time, combined with data from real internal panel climate recordings. The new model shows how ageing time under an artificial climate corresponds to natural ageing time. The designer can now choose a climate combination and exposure time, covering the planned lifetime for his building. It can also be seen from the obtained results that it can be very problematic to predict future performance by extrapolating test results. Extrapolation of the 70°C and 60 % humidity result would lead to prognostication of failure in a short period of time. It is, therefore, recommended to choose an adequate ageing scenario instead.

5.5 PUR cores

Currently, polyurethane is the most popular of sandwich panel core materials. This is due in particular to the reason that when PUR foams develop, the rising foam has very good auto adhesive abilities and, therefore, sticks directly to the panel faces. PUR raw materials are furthermore relatively inexpensive, which makes the product cheaper than, for example, mineral wool core panels. This chapter describes the background of sandwich panel production with PUR core. This includes basic information on polymerization processes, which are by far more complex than in the previously described polystyrene foams. In a next step, gathered information on the durability performance of PUR foams from other fields of application is presented. Although these fields are not directly comparable to the sandwich panel application, the presented results show that PUR foams deteriorate and change properties over time. Such change in properties must be caused by chemical changes in the polymeric structure. Possible reactions splitting the polymer are presented. They show that the presence of oxygen is necessary to split PUR polymers. Directly after the production process, the cellular PUR matrix is, however, filled with carbon dioxide, a side product in the
polymerization reaction, and blowing agent. Only with time, oxygen diffuses into the cells. The speed of gas diffusion into PUR foams has been described previously in other contexts. Such diffusion speed, however, is used in this research for the first time in the context of durability. The diffusion speed depends on the temperature and the geometry of the investigated foam. For the first time, this makes it possible to find a correlation between oxygen diffusion in full scale panels under ambient temperatures and small scale samples under elevated temperatures in a climate cabinet. The result is a conversion chart that allows the determination of how long a small scale sample must be exposed to a chosen climate to simulate a given time under ambient conditions.

5.5.1 Introduction to PUR polymers

Polyurethane (PUR) is by far the most popular core material for sandwich panels. It combines adequate mechanical performance with a moderate price for raw materials and a relatively easy production technique. In principle, a mixture of three components is used to form PUR:

- Isocyanate – NCO
- Polyol / Polyamine – OH / – NH₂
- additional substances

Modern sandwich panels are produced in a continuous process. The three foam components are blended in a mixing head and the composition is injected between the two panel faces. After a short curing period, the continuous sandwich panel is cut to the required length. The finished panels are then stacked for further curing, which may take up to several hours, and, after that, are packed for transportation. This effective production process allows facility speeds of 9 m/min and more.
Polyurethane, unlike other plastics, is never a “pure” synthetic product (Uhlig, 2001). While, for example, PVC consists solely of chains of vinyl chloride or PET of chains of ethylene, PUR is always a mixture of different polymers. The urethane group in most PUR polymers is of minor importance and even “PUR” products, lacking the urethane group completely, are known. However, all variations have the chemistry of isocyanates in common. The properties and characteristics of PUR are not essentially influenced by the distinguishing marks of urethane, but by other various impacts, leading to an immensely wide field of different plastics for multiple applications.

It is the isocyanate-group –NCO within the isocyanate that is responsible for its high reactivity and energy. It reacts in an exothermal way with any hydrogenously active substance, for example alcohol –OH or aminos –NH₂. Under the right conditions, Isocyanate can even react with itself. A reaction with an organic acid (–COOH) produces carbon dioxide. Furthermore, the isocyanates, when not used up completely can react with a primary reaction product and form a secondary reaction product. This second reaction can have a great influence on the outcome of the process (Uhlig, 2001).
When reacting with itself, the isocyanate forms polyisocyanurate (PIR), a product showing enhanced fire performance compared to PUR. It is, therefore, often used in the construction industry and is becoming more and more important for the sandwich panel industry. Today almost all foams used in sandwich panel construction are PIR modified PUR foams. This means their polymer is a mixture of PIR and PUR. However, the PUR characteristics are predominant in most types of foam. Polyurethane is generally distributed to the producers in the three components mentioned earlier. These components are then mixed in the manufacturing process for the reaction to take place. During the reaction different typical phases can be observed.

- **Mixing phase:** Here the components are mixed. It is the time of the first contact of the reacting components \((t = 0)\).

- **Cream time:** The cream time is the space of time from the mixing of the components \((t = 0)\) until the first reaction results can be observed. This is the time span the mixture is usually handled. As the name indicates, the mix has a creamy consistency and high viscosity. The first changes that can be noticed are a change in viscosity and an expansion of volume. During this time the temperature rises rapidly to up to 150°C.

- **Setting time:** It is the time span between \(t = 0\) and the first appearance of increasing rigidity of the mix.

- **Rising time:** This is the time when the unhindered expansion of the PUR reaches a maximum.

- **Tack-free time:** This is the time difference from \(t = 0\) until the developing PUR foam has lost its adhesive abilities.

Depending on the type of reaction and on the mixture in use, the time spans described above can vary from a few seconds to several minutes. However, the last step does not indicate that the chemical reaction has come to an end yet. During the maturing phase, which can last for days or even weeks, the reactions within the foam go on. This process can be influenced by temperature and humidity. The optimum foam properties are only reached at the end of this process. The panels are cut directly after the curing process, which means only minutes after the injection between the faces, most of the maturing must have taken place by then. The cutting applies a considerable stress to the panel core. The faces are pulled and ripped by the saw blade and the core has to be strong enough to withstand such impact without damage.
Research into the development of the bonding strength in PUR polymers has been undertaken by Gaudeus (2005). Though this research is primarily on PUR based glues used for mineral wool core panels, the results indicate that the curing of the polyurethane advances very rapidly.

![Graph showing bonding strength development in sandwich panel for two PUR foam glue systems](image)

**Fig. 5-27** Development of bonding strength in sandwich panel for two PUR foam glue systems

The quality of the foam can be adjusted by the producer. The first and most important adjusting possibility is the density of the foam. Using a bigger amount of mixture on the same panel area leads to an increased foam density. Up to the beginning of 2004 a minimum foam density of 40 kg/m\(^3\) has been required in sandwich panels. The current opinion was that only foams with that minimum density provide sufficient stability for use in a sandwich panel. In order to minimize the use of raw material, efforts were made to produce foams at lower densities with adequate mechanical strength. Today there are foam systems on the market going down to as little as 36 kg/m\(^3\) in density. Another way of foam optimization is the admixture of additives that help to control the polymerization reactions. A variety of products are on the market varying considerably in price and quality. The process of continuous PUR sandwich panel production has become extremely sophisticated over the last decades. Producers report that about 150 different parameters in the production line are constantly recorded and can be adjusted. This includes band speed, mixing ratio of isocyanates, polyole and additional substances, temperature of the components (including face temperature), temperature of the double belt, and many more. The variety of foams produced is, therefore,
immense. Such a large variety of parameters makes an evaluation of durability of each type of foam necessary. Each parameter can have a potential influence on the long term performance of the foam.

Nevertheless, the basic chemistry of all PUR foams is the same. In order to be able to understand the ageing of a full PUR core sandwich panel, it is necessary to have a look at the chemical background and possible degradation reactions of the polymeric structure in the core material.

### 5.5.2 Ageing in PUR polymers

In the past, the long term performance of polyurethane has only been a small concern in sandwich panel construction. When continuously produced PUR sandwich panels were introduced in the early seventies, the subject was not a major topic in approvals and relevant building regulations. Other fields of PUR foam application were, however, more aware of time-dependent changes in polyurethane properties. Examples are given in the following.

**Flat roof application**

Some knowledge is gathered through investigations into PUR used as insulating material in flat roof applications (Götze, 1988). Here PUR insulating slabs were extracted from a roof after 20 years of service. Although no problems were reported, the sealing layer of the roof needed refurbishment and the producer of the foam system investigated the state the foam had been in after two decades of use. Good dimension stability and good compression capacities were found. These two properties are important for the insulation layer in a conventional flat roof. The report is, however, lacking the initial strength values and, therefore, does not allow a comparison between initial and remaining compressive strength after 20 years.

**Bayer Igloo**

In 1961 Bayer built an igloo solely from PUR foam at their site in Leverkusen, Germany, using a gap filling foam glue that had been newly developed at that time. Gap filling foam glue is a PUR foam provided in a pressurised dispenser that is, for example, used for fitting and sealing window frames. The igloo was physically not covered in any way and stood in all weathers without protection. In particular, no protection from ultraviolet light was provided. After 25 years the igloo was torn down and samples were taken and tested (Zehender, 1986). Before testing, a “brown layer” was taken from the specimen. A change from creamy white of fresh PUR foam to a rather brownish colour over time was reported. The effect was
particularly strong on the outer layer of the foam, where the foam was exposed to direct sunlight. The global radiation obviously caused an oxidation reaction as described in chapter 5.1.3 of this report. The obtained results showed that the performance in compression and heat transfer were still sufficient to meet valid requirements. No comparison with the initial values is provided so that no statement on the loss of strength can be made.

**Long-distance heating system application**

Pre-insulated bonded pipes have been used in long-distance heating systems for more than 30 years. The pipes are made from an inner steel pipe, an insulating layer of polyurethane, and an enveloping outer casing of polyethylene. Like in a sandwich panel, the three layers are bonded together, making use of the auto adhesion ability of the expanding foam core during production. The three members then act together structurally. The temperature of the medium transported through the pipes can rise up to 140°C, although normal operating temperatures are around 90°C (Hoffmann, 2002). The expected life cycle of a pipe is 30 years. In Hoffmann’s research pipes were dug up after 30 years and examined. The results show that temperature is the determining factor when looking at ageing in the PUR layer. A change in colour from the initial creamy white to brown or sometimes even black has been observed especially near the inner steel pipe where the highest temperatures are reached. Towards the outer regions the intensity of change in colour decreases. Together with the change in colour, Hoffmann reports an increasing brittleness of the polyurethane. Testing has shown that this brittleness has lead to increased tensile strength between foam and steel pipe. At the end of the pipe systems, where the foam is in direct contact with the atmosphere, more dramatic changes in colour and structural performance have been observed. Changes in gas concentration inside the foam are held responsible for the dramatic change. The described pipes in many aspects compare to sandwich panels:

- The bond between face and core is necessary for the stability of the system.
- The core is protected from environmental influences through coverings.
- One face (in the pipes it is the contact area to the internal pipe) is subject to high temperatures. While in sandwich panels temperatures increase to around 90°C (see chapter 5.2.1), the pipes are subject to around 140°C.

The major difference when comparing the two systems is however, that the pipe is protected almost completely from the atmosphere. It is only at the end of the pipe, where there is a contact zone between the surrounding atmosphere and the PUR layer. In sandwich panels this
contact area is much larger, as the panel is in constant contact with the atmosphere at its edges. The influence of the surrounding atmosphere, therefore, needs to be considered in durability considerations for sandwich panels.

In order to predict the time dependent changes in heating systems, full scale accelerated ageing tests on specimen of 3 m length are performed (prEN 253). The pipes are loaded with liquids that are heated to either 160°C for 3,600h or 170°C for 1,450h. After the exposure, the specimens are tested structurally until failure. The minimum life expectancy is generally set to be 30 years and, making use of the Arrhenius relation, the performance can be predicted on the base of the testing results. Unfortunately, such a testing scenario is not adaptable for PUR foams used in sandwich panels. The Arrhenius approach presumes that the investigated specimen can withstand a temperature that is well above the expected service temperatures. Only an elevation of test temperature above the service temperature ensures that all deterioration reactions that can occur in practice are accounted for by the test. It is furthermore necessary to accelerate the deterioration speed by choosing temperatures above the service temperature. Such a procedure is impossible with sandwich panels, as these tend to disintegrate at temperatures little above service temperatures. For sandwich panels, a different approach has to be chosen.

### 5.5.3 Possible degradation reactions of polyurethane

To develop an ageing method for sandwich panels, it is important to look at possible degradation reactions in the PUR foam first. It has been demonstrated before (see chapter 5.1.3) that oxidation reactions of the polymeric structure are held responsible for the deterioration in mechanical strength. Just like in a fresh cut apple, such oxidation reactions are responsible for the brownish colour in the foams. A break in the polymeric structure must influence the structural performance of the foam. In the following, some of the known deterioration reactions for polyurethane are presented.

First possibility is the oxidation of the ether group with oxygen. This may be shown by:

\[
R-\text{CH}_2\text{O}-\text{CH}_2\text{R} + \text{O}_2 \rightarrow R-\text{CH}_2\text{O}-\text{O}-\text{CH}_2\text{R}
\]

*fig. 5-28 Ether group in polymer reacts with atmospheric oxygen and forms unstable compound*
The break of the polymer in the presence of oxygen leads to an unstable compound. In the presence of small amounts of water or vapour, the binding breaks down completely.

\[ R-CHO-O-O-CHR' + H_2O \rightarrow R-CHO-OH + HCO-CHR' \]

fig. 5-29 complete break of polymer with small quantities of water

A second possible reaction destroying the polymer is the hydrolysis of the ester group. In the presence of water the polymer chain breaks.

\[ R-C-O-R + H_2O \rightarrow R-C-OH + HO-R \]

fig. 5-30 hydrolysis of ester group in the presence of water

It is also possible that the polyurethane group itself breaks under the presence of vapour.

\[ R-O-C-N-R-N-C-O-R' + H_2O \rightarrow R-OH + HO-C-N-R-N-C-O-R' \]

fig. 5-31 hydrolysis of the polyurethane group under the presence of water

The unstable reaction product in a secondary reaction breaks down to:

\[ HO-C-N-R-N-C-O-R' \rightarrow R-OH + CO_2 + H_2N-R-N-C-O-R'' \]

fig. 5-32 polyurethane group breaks after hydrolysis reaction

Chemical experts, dealing with the subject of PUR deterioration, doubt that the reactions illustrated in figure 5-30 to figure 5-32 are likely to occur in a sandwich panel under normal end use conditions. The oxidation reaction is also excluded under the assumption that oxygen
is not available inside a sandwich panel. This is, however, true for fresh panels only. With time, oxygen from the surrounding atmosphere penetrates the panel. The process is described in detail in the following, as it explains the deterioration of mechanical properties and allows a connection to be established between natural foam ageing and accelerated ageing in a climate cabinet.

5.5.4 Diffusion of cellular gases in PUR matrix

Immediately after the production process, the cellular matrix of PUR (see fig. 5-33) is filled with a mixture of carbon dioxide, as a side product of the polymerisation process, and the used blowing agent. These high concentrations of gases strive to equalize with the surrounding atmosphere. This means that the carbon dioxide and blowing agent want to escape from the cell matrix into the atmosphere while oxygen and nitrogen together with smaller amounts of other gases try to penetrate the cells. Such diffusion can happen at the open edges of a panel only. The steel faces protect large areas of the panel from diffusion.

![fig. 5-33 closed cell structure of a PUR polymer matrix, taken from IVPU (1998)](image)

For every gas, the ability to diffuse through the cell walls differs considerably. In particular, carbon dioxide is able to escape from the cell relatively quickly. In the past this has lead to problems with sandwich panels, as unequal pressure compensations lead to partial under or sometimes over pressure in the cell matrix. For solely CO$_2$ blown panels, it was the large under pressure caused by the fast escape of carbon dioxide that has lead to unacceptable dimension changes.

The changes in cellular gas composition have two long term effects on the sandwich structure:

1. As the production process or PUR foam is exothermic, there is always low pressure in the cell matrix after the cooling process. It has been shown (Walter and Wendel, 1992)
that this under pressure can be as low as 0.7 atm\(^{17}\). Low pressure can affect the tension capacity in the small scale tension tests, as well as the compressive strength. It constitutes an additional stress on the cell structure that can either add to the sample strength (tensile strength) or lower the observed strength (compressive strength). At a found internal pressure of 0.7 atm, the pressure difference between the internal cells and the surrounding atmosphere is 0.3 atm. The influence on cross panel strength is thus roughly 0.03 N/mm\(^2\). Compared to a standard cross panel tensile strength which, for a PUR sample, is usually between 0.1 and 0.15 N/mm\(^2\), the contribution of the low pressure is between 20 and 30% of the total strength. Lacking further information on actual internal gas pressures, the effect is neglected in further considerations but has to be kept in mind when evaluating possible shortcomings of the presented results.

2. The possibility of oxidation processes in the cell polymers is dependent on the presence of oxygen. The presence of high temperatures and oxygen can induce the chemical decomposition of PUR polymers as has been presented in chapter 5.5.3. This effect shall now be used to find a connection between real time ageing and accelerated laboratory ageing. Such connection is established by presenting a mathematical solution describing the diffusion processes of oxygen into the cell matrix and comparing the process in full scale panels under ambient conditions with small scale test specimen under evaluated temperature conditions. It will be shown that the intake of oxygen depends on two important factors, the geometrical shape of the specimen and the surrounding temperature.

### 5.5.5 Mathematical model

As the changes in cell gas composition are also important for other core properties, particularly the change of insulation ability over time, it has been tried previously to predict the diffusion processes mathematically (Walter and Wendel, 1992). Mathematical models adopt the theories for heat currents or moist currents (drying of porous materials). For development of a mathematical model, the following simplifications are agreed on:

- The changes in cellular gas composition are effected solely by gas diffusion
- The gas diffusion process is determined solely by the partial gas pressure differences; i.e. other present gases do not influence the diffusion of the observed gas

\(1\text{ atm} = 1\text{ atmosphere} = 1013\text{ hPa} = 1.013\text{ bar}\)
As a simplification, the diffusion coefficient \( D_{eq} \) is taken as a mean value over the total thickness of the foam matrix.

The non linear dynamic diffusion process in a three dimensional matrix is then described by Fick’s 2\textsuperscript{nd} law:

\[ \frac{\partial p}{\partial t} = D_{eff} \left( \frac{\partial^2 p}{\partial x^2} + \frac{\partial^2 p}{\partial y^2} + \frac{\partial^2 p}{\partial z^2} \right) \]

where
- \( p \): partial gas pressure
- \( t \): time period
- \( x, y, z \): geometric coordinates
- \( D_{eff} \): effective diffusion constant for particular gas

For a one-dimensional diffusion process this equation simplifies to:

\[ \frac{\partial p}{\partial t} = D_{eff} \left( \frac{\partial^2 p}{\partial x^2} \right) \]

This model adequately describes situations with a single exposed side (scenario A, see fig. 5-34) and two exposed sides (scenario B, see fig. 5-36). For a sandwich panel of considerable length, the size in lengthwise direction can be seen as infinite (generally between 6 to 10 meters) compared to the width, which is generally a little more than 1 meter. The model is then sufficient to describe the diffusion processes into a full scale sandwich panel.

For a cuboid with two sealed faces (scenario C, see fig. 5-38), as, for example, a small scale tension or compression test specimen, the model is no longer sufficient. A two dimensional approach needs to be made. Fick’s law changes to:

\[ \frac{\partial p}{\partial t} = D_{eff} \left( \frac{\partial^2 p}{\partial x^2} + \frac{\partial^2 p}{\partial y^2} \right) \]

Here the \( x \) and \( y \) coordinates represent the width and length of the small specimen (generally 100 by 100 mm). A comparison of the two approaches shows that the geometry of the analyzed sample together with the effective diffusion constant, which is temperature depending, determine the speed of gas and, particularly important for this research, the speed of oxygen penetration into the sandwich sample.
Mathematical solutions for the two models are found in literature. They are presented in brief in the following.

5.5.5.1 Time dependent changes in cell pressure

In accordance with Walter and Wendel (1992) the partial pressure of a gas at a given point in the PUR matrix is given by:

\[ p_i = p_{oi} + (p_{ai} - p_{oi}) \cdot F_i(x,t) \]

where

- \( p_{oi} \): partial pressure in surrounding atmosphere
- \( p_{ai} \): partial pressure in matrix at \( t = 0 \)
- \( p_i \): partial pressure after time span \( t \) at distance \( x \)
- \( F_i(x,t) \): diffusion factor covering sample geometry, diffusion constant and location of considered point in the matrix

Knowing the oxygen concentration in the cells immediately after production \( (t = 0) \) and that the concentration in the surrounding atmosphere is the maximum concentration that can be reached, leaves factor \( F_i(x,t) \) as the decisive factor for internal concentration. The factor covers the geometry of the considered sample and includes the diffusion constant, which is dependent on the examined gas and foam material combination, as well as the temperature during the diffusion process. Higher temperatures cause faster diffusion processes. Solutions for the different geometries important to this research are presented in the following.

5.5.5.2 Single open side

A single open side scenario assumes that the sandwich core is sealed from diffusion at all edges except for one (see fig. 5-34). Assuming that panel joints are not completely airproof, this scenario is in principle not found in practice for sandwich panels, but the solution is presented here for completeness.
The diffusion factor for this scenario is given by Walter and Wendel (1992) as

\[ F(x, t) = \frac{2}{\sqrt{2\pi}} \int_0^\infty e^{-\xi^2} d\xi \]

where

\[ \xi = \frac{x}{\sqrt{2 \cdot D_{eff} \cdot t}} \]

The development of the diffusion factor \( F(x, t) \) over the factor \( \xi \) develops as illustrated in figure 5-35.
Considering equation 5.5-4 in combination with the results presented in figure 5-35, shows that when the factor $\xi$ is big, which is the case when $x$ is big, meaning that the considered point is far inside the matrix, the partial gas pressure of oxygen is zero ($F_{(t,x)} = 1$). When the considered time increases, $\xi$ decreases and the oxygen content, therefore, increases. The same happens when the considered point is moved closer to the exposed edge of the system.

### 5.5.5.3 Two open sides

A more realistic scenario for a sandwich panel is a scenario with two sides that are diffusion free. This model represents a sandwich panel of considerable length that is equipped with two diffusion tight faces. The principle setup is illustrated in figure 5-36. Note that, compared to the model presented before, the origin of coordinates ($x$) has been moved to the middle of the panel.

For this model the diffusion factor is given according to Walter and Wendel (1992) by

$$F_{(t,x)} = \frac{4}{\pi} \left[ \cos \left( \frac{\pi \cdot x}{a} \right) \cdot e^{-\xi} - \frac{1}{3} \cdot \cos \left( \frac{3\pi \cdot x}{a} \right) \cdot e^{-3\xi} + \frac{1}{5} \cdot \cos \left( \frac{25\pi \cdot x}{a} \right) \cdot e^{-25\xi} \right]$$
where

\[ \xi = \frac{D_{\text{eff}} \cdot t}{a^2} \]

- \( a \): width of the panel
- \( x \): \( x = 0 \) at middle of panel and \( x = a/2 \) at the face open to diffusion

For this configuration and assuming \( x = 0 \), the development of the diffusion factor \( F_{i(x,0)} \) over the scenario specific \( \xi \) factor is illustrated in figure 5-37.

Because of the changed point of origin, the \( F_{i(x,0)} \) factor inverts. This means that - and again figure 5-37 is only true for the coordinate \( x = 0 \), which is the centre of the sample - at the beginning of the consideration \( (t = 0) \), the factor \( \xi \) is small and the oxygen concentration, therefore, is zero. Only with increased time and dependent on the total width of the sample \( (a) \) does the oxygen content increase. Such a relationship can be established for any considered point in the sample and for samples of any chosen width.

For samples with four sides open to diffusion, such as small scale samples used in cross panel tensile tests, this model is not sufficient. An adequate model is described below.

### 5.5.5.4 Four open sides

The geometry of a sample with four open sides is illustrated in figure 5-38. The samples projection must not necessarily be of square shape although this is mostly the case with
samples used for determination of cross panel tensile strength and compressive strength. Here again, the origin of the applied coordinate plane is located in the centre of the sample. The distances from the centre to the edges of the sample in $x$ direction are $a_1$ (positive orientation along $x$ axis) and $a_2$ (negative orientation along $x$ axis). For the special case of a sample of square projection shape, the lengths are equally long and thus the width of the sample is $2a$. The same consideration is true for the length of the sample. The diffusion factor $F_i$ is no longer only dependent on one direction ($x$) and time, but now implements a second geometrical direction ($y$) and thus changes to $F_{i(x,y,t)}$.

![Diagram](image)

**Fig. 5-38 diffusion model with four open sides (hatched area is in contact with atmosphere)**

In accordance with Newman (1931) the diffusion factor $F_{i(x,y,t)}$ is given by

$$F_{i(x,y,t)} = \frac{4}{\pi} \left[ \frac{1}{3} \cos \left( \frac{\pi x}{2a} \right) e^{-t} + \frac{1}{5} \cos \left( \frac{3\pi x}{2a} \right) e^{-2t} + \frac{1}{5} \cos \left( \frac{5\pi x}{2a} \right) e^{-3t} \right] \frac{4}{\pi} \left[ \frac{1}{3} \cos \left( \frac{\pi y}{2b} \right) e^{-t} + \frac{1}{5} \cos \left( \frac{3\pi y}{2b} \right) e^{-2t} + \frac{1}{5} \cos \left( \frac{5\pi y}{2b} \right) e^{-3t} \right]$$

**eq. 5.5-9**

where

**eq. 5.5-10**  
$$\xi = D_{\text{eff}} \cdot t \cdot \left( \frac{\pi}{2a} \right)^2$$

**eq. 5.5-11**  
$$\upsilon = D_{\text{eff}} \cdot t \cdot \left( \frac{\pi}{2b} \right)^2$$

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with

\[\begin{align*}
    a: & \quad \text{width of the specimen} \\
    b: & \quad \text{length of the specimen} \\
    x: & \quad \text{distance in width from the middle of the specimen} \\
    y: & \quad \text{distance in length from the middle of the specimen}
\end{align*}\]

For this model and assuming \(x = 0\) and \(y = 0\), which is a point in the centre of the sample, the \(F_i\) factor over the scenario specific \(\xi\) factor develops as follows.

\[F_{i(x,y,\theta)}\]

**fig. 5-39 development of diffusion factor \(F_{i(x,y,\theta)}\) over scenario C specific factor \(\xi\) which includes information on sample geometry and time passed.**

Very much like in the example with two open sides described previously, the oxygen contents at the beginning of the considered time period is zero and increases with time or when the considered point moves towards the edge of the sample. Compared to the previous example, the oxygen content rises faster as diffusing gas from all four sides of the sample accumulate.

All the models are dependant from the diffusion constant. The dependency of that constant on temperature and the considered gas and matrix combination is discussed in the following.

### 5.5.6 Temperature dependent changes in diffusion constant

Generally, it can be distinguished between self diffusion and extrinsic diffusion. Self diffusion describes a process where at a temperature \(T > 0^\circ\text{K}\) atoms in a matrix have different energetic states. The allocation of energy levels follows the Gauss normal scatter. There are some atoms with high levels of energy. Most atoms have a medium energy level and other are at a low energy level. By changing the position in a matrix, these different states are compensated.
The more important diffusion is, however, the extrinsic diffusion. Here, two different levels of concentration try to equalize. The process is time and temperature dependent. The time dependency is covered by the previously described Fick's law. The temperature dependency is implemented in the diffusion factor $D_{\text{eff}}$ (see fig. 5-40) and can be described, using the Arrhenius function.

\[
D_{\text{eff}} = D_0 \cdot e^{-\frac{Q}{R T}}
\]

where

- $D_{\text{eff}}$: Effective diffusion coefficient for particular gas at particular temperature [m$^2$/s]
- $D_0$: Diffusion constant [m$^2$/s]
- $R$: Gas constant (8.314472 J/mol·K)
- $Q$: Activation energy [J/mol]
- $T$: Temperature [°K]

![fig. 5-40 temperature dependency of diffusion coefficient; illustration of connection to activation energy](image)

For a PUR matrix, effective diffusion coefficients for some temperatures can be found in literature. To be able to calculate the diffusion coefficient for any temperature, it is necessary to determine the activating energy, as well as the diffusion constant from the available results. This can be done by adding logarithm to equation 5.5-12, which then changes to
eq. 5.5-13  \[ \ln D_{\text{eff}} = \ln D_0 - \frac{Q}{RT} \]

respectively

eq. 5.5-14  \[ \log D_{\text{eff}} = \log D_0 - \left( \frac{Q}{R T} \right) \]

With this straight line equation of \( D_{\text{eff}} \) as a function of temperature (\( \log D_{\text{eff}} = f(T) \)), the activation energy \( Q \), the gradient of the line, and the diffusion constant \( D_0 \), which is the point of intersection with the ordinate, can be determined (see fig. 5-41).

![fig. 5-41 logarithmic temperature dependency of diffusion coefficient](image)

Knowing two points on the straight line, it is now possible to calculate the diffusion constant \( (D_0) \) for a given gas at any given temperature. Pairs of diffusion constants for important gases in PUR matrixes are given below.

<table>
<thead>
<tr>
<th>table 5-8 effective diffusion constants for two temperatures</th>
</tr>
</thead>
<tbody>
<tr>
<td>Effective Diffusion coefficient ( @ 10^{-13} [\text{m}^2/\text{s}] )</td>
</tr>
<tr>
<td>Temperature</td>
</tr>
<tr>
<td>-------------</td>
</tr>
<tr>
<td>23°C</td>
</tr>
<tr>
<td>70°C</td>
</tr>
</tbody>
</table>

The activation energy and frequency factor can then be calculated to the following.
Having compiled mathematical solutions to determine the geometrical influence of diffusion speed into a PUR matrix, as well as solutions for the temperature influence on the diffusion, it is now possible to compare the oxygen contents of small scale samples ageing in climate cabinets at elevated temperatures with full sandwich panels under natural conditions.

5.5.7 Comparison of diffusion process between small and large scale samples

It is the aim of this next section to develop a simple conversion chart, which allows a comparison of oxygen levels in a small scale sample and a full scale panel. This is done by determining oxygen levels for important points in the small specimen, as well as in the full panel. The important difference between the two samples is their geometry and their surrounding temperature.

5.5.7.1 Cuboid (small scale sample)

The temperature of the small scale sample is assumed to be 70°C in average. The specimen has an edge length of 100 mm by 100 mm. Four sides are diffusion free while the upper and lower side is sealed through the remaining metal face.
Figure 5-42 shows the development of the oxygen content at two points in the cuboid. The red line indicates the centre of the cuboid. The blue line shows the development at a point in the four edges of the cuboid, 10 mm from each side. The period displayed is one year. After one year the diffusion process of oxygen for a 100 by 100 mm cuboid at a temperature of 70°C \( (D_{eff} = 10 \cdot 10^{-11}) \) is completed. This means that the partial pressure of oxygen inside the panel is equal to the partial pressure of oxygen outside the panel. For the point at the edge of the cuboid, this state is reached earlier, approximately after 150 days. For the time period of 90 days, which is used during most ageing procedures, it can be said that the diffusion in oxygen is not completed for the whole specimen if the exposure temperature is 70°C. When looking at the centre of the sample, the oxygen content is about 62% compared to the surrounding atmosphere.
5.5.7.2 Full panel

The in situ panel is assumed to have a width of 500 mm. Its average temperature is assumed to be 23°C ($D_{\text{eff}} = 1.7 \cdot 10^{11}$). Panel length in comparison to panel width is assumed to be infinite. Therefore, only the sides of the panel are diffusion free.

![Diagram showing the development of oxygen contents for three distances joint edge in 500 mm wide panel. Note: the length of the panel is assumed at infinite and thus do not influence the process.](image)

The examined time period here is 100 years. Even after this long time, the diffusion process has not come to an end. Especially when looking at the centre of the panel, it can be noticed that, only after a period of roughly 5 years, the oxygen content begins to rise significantly.

When changing the panel width to 1 metre, which is the most common size found in regular sandwich panels, the graph changes to the following.
fig. 5-44 development of oxygen contents for three distances from cut edge in 1000 mm wide panel

It now takes some twenty years for the first oxygen to reach the centre. Even after a period of 100 years, the diffusion process is far from being complete. The flatter ascent in the "50 mm distance from side" curve in figure 5-44 compared to figure 5-43 is due to the fact that, at this point, more gas needs to be passed to the inner cells. The inner cells "suck" the oxygen away from the outer cells and the gas level in the outer cells is, therefore, smaller compared to the previously described smaller sample.

5.5.7.3 Conversion tables

The combination of the previously described scenarios leads to a tool where the oxygen content of the small scale cuboid at elevated temperatures and the full panel under ambient conditions can be compared. In figure 5-45 the time scale of the small scale panel is factorized with one hundred. The two scenarios compared here are the 100 mm edge length cuboid at 70°C and the 500mm panel at 23°C.
The chart can be used by choosing a "life cycle period" for the sandwich construction, in this case 50 years (1). The intersection on a vertically drawn line (2) with the oxygen content curve for the full panel must be found (3). From here a horizontal line (4) to the small scale test cuboid graph is drawn. At the point of intersection (5) the oxygen contents in the middle of both samples are equal. A vertical line (6) back to the time axis gives the result, which in this case equals 22.

As the time axis for the small cuboid was factored, the result is:

\[ \text{Conversion:} \quad \frac{\text{reading}}{100} \cdot \frac{365}{100} = \frac{22}{365} \approx 80 \]

Corresponding ageing condition for cuboid: 80 days at 70°C

For the more frequent scenario of a 1000 mm wide panel, the relation is described in figure 5-46 below. The time period is prolonged to two hundred years. All other parameters are kept as previously described.
Assuming a “life cycle period” of 100 years leads to an ageing time of approximately 62 days. Using the same principle, it is possible to calculate all combinations of test specimen geometry (sample size) and full scale panel geometry. This can also be done for any temperature combination. It has to be kept in mind that the conversion tables presented here only compare the centre points of the evaluated samples. Due to the geometry of the compared specimen, such an assumption is, from a design point of view, a safe approach. When looking at the full cross section, the oxygen content per area in the small scale cuboid is bigger than in the full scale panel. Thus the ageing has proceeded further in the small sample. The mechanical strength properties determined on the small sample are therefore implementing a longer ageing effect than would have been observed in the full panel. At the same time it is currently unclear how the content of oxygen inside the cells transfers into deterioration. It may be that even small quantities of oxygen are sufficient to kick off the degradation reaction and an increase thereafter has little influence. Nevertheless some of the entering oxygen is used up in the reaction. Further clarification from chemical experts is needed.

PUR core samples were exposed to a variety of climates in this research. The results from the cross panel tensile tests are presented in the following.
5.5.8 Results from cross panel tensile testing

As PUR cores are the most popular sandwich panel cores in the market at the moment, the choice of samples for the cross panel tensile testing was enlarged for this type of core material. Two kinds of blowing agents were investigated:

- Panels with CO$_2$ blown core
- Panels with pentane blown core

At the beginning of this research, carbon dioxide blown PUR foams were new to the market. New legislation forced the producers to substitute their blowing agents that destroy the ozone layer (HCFC) with environmentally friendly gases. Carbon dioxide, a gas that develops during the PUR polymerization as a by-product, was seen as the ideal substitute. At first, the process seemed successful, after problems with dimension stability caused by rapid diffusion of CO$_2$ from cell matrix (see table 5-8) were solved. In the last years, however, it has been discovered that foams with similar structural performance but at lower foam density can now be produced with pentane as a blowing agent. This saves raw material and pentane blown panels have since been sold at a cheaper price. Carbon dioxide blown panels have, therefore, vanished from the market. Nevertheless, carbon dioxide blown panels are included in this research. The results from cross panel tensile tests after exposure to a variety of artificial climates are presented in figure 5-47.

![Graph showing results from cross panel tensile test on aged PUR core samples with CO$_2$ blowing agent.](image)

fig. 5-47 results from cross panel tensile test on aged PUR core samples with CO$_2$ blowing agent.
For the cross panel tensile tests, fresh samples were distributed to external laboratories to conduct the exposure to artificial climates. Only the exposure to 90°C and low humidity was undertaken in Mainz. The samples where then returned to Mainz where the cross panel tensile testing was conducted. Exceptions were the samples aged at 65°C / 100% RH and 50°C / 90% RH. These were tested in an external laboratory.

The rapid loss in strength for the panels not tested in Mainz attracts attention. A possible explanation for the effect is that all samples were exposed to the artificial climates without a silicone sealing around their edges. Such a sealing can be provided, according to prEN 14509, to hinder moisture from penetrating the intersection between face and core during the accelerated ageing procedure. The penetrating moisture can cause deterioration of the back-face coating. It is open to conjecture if such sealing simulates the real on site scenario. On the one hand most longitudinal panel joints are designed with the metal sheet cut edge bending back into the foam (see fig. 5-48).

\[\text{fig. 5-48 cut end of metal face penetrates back into core in typical cross section}\]

If the aim is to simulate this situation, lacking silicone is probably a scenario that is too severe. The same is true for any area inside the cross section of the panel. On the other hand sandwich panels are cut to length directly after the production process. These cut edges are completely open to the environment. Here the temperature and humidity can attack the face-core intersection uninhibited. Whether a lacking silicone protection in an ageing test is appropriate or not is simply a question of longitudinal to transverse joint length in a particular panel. It is, however, always a worst case scenario to omit the silicone sealing.

The testing in this research also discovered that the deterioration of the back face coating is likely to be the reason for a drastic loss in cross panel tensile strength. Especially the samples aged at 90°C and 60% RH showed a tendency to loose connectivity between coating and the
actual steel face. The effect became visible only in the tests after 56 days of exposure and were even more dramatic after 90 days of exposure. Unfortunately, accurate reporting on failure modes are lacking for the 65°C / 100% RH and 50°C / 90% RH samples because these were tested externally. Yet it seems plausible that the drastic loss in cross panel tensile strength for these samples is caused by deterioration of the back-face coating.

When looking at the pentane blown samples, the results are even more dramatic (see fig. 5-49)

![Figure 5-49](image)

**fig. 5-49 results from cross panel tensile test on aged PUR core samples with pentane blowing agent**

It is particularly peculiar that the results for a climate (50°C / 80% RH), not so severe, show a dramatic loss in strength while the obtained results for a rather more severe climate (65°C / 100% RH) show almost no change at all. It is also almost a typical pattern for many PUR samples that, after an initial drop in strength, the panel seems to recover and, on occasions, regain much of its initial strength. This ageing pattern, which is difficult to describe, could be a motive to challenge the obtained results, had not other scientific work, as, for example, the ASPAN research or investigations conducted by Just (1995) shown similar results (see fig. 5-50). Both investigations also struggle with interpretation of the obtained results for PUR ageing.
There are several possible reasons for the obtained results:

1. “Fresh” sandwich panels were taken for the initial testing. “Fresh” in this context means that they were delivered to the testing laboratory more or less directly after production. It has been mentioned before that the polymerization process inside the PUR matrix has not come to a complete end until several days after the production. Unfortunately, there is no information available on how the panel strength develops during such curing phase, though figure 5-27 suggests that after 24 hours of curing close to 100% of the final strength is reached. It may now be that the samples were tested or exposed to the artificial climates before the curing process has come to a complete end.

2. During the earlier discussion of the diffusion processes, it was pointed out that, directly after the production process, there may have been significantly low pressure in the cell matrix. This low pressure tries to equalize with the surrounding atmosphere. While the initial under pressure adds cross panel tensile strength to the sample, the effect is getting smaller with the pressure differences equalizing. Again, such an effect has never been investigated and, although diffusions can be calculated, it is uncertain what initial low pressure is present in a sample directly after the production.

3. The oxidation reactions of PUR polymers during the ageing process are to a large extent unknown. It is, however, possible that decomposition products can react with each other or even with the not completely cured fresh foam and form a secondary polymeric structure. Such polymers may or may not increase the strength of a sample or they may increase the strength at some point in the ageing process but decrease after prolonged ageing.

4. It has been reported for some PUR cores that the combination of high temperatures and saturated air has a severe effect on the dimension stability. Such observations have
also been made during this research. This effect is possibly caused by a very rapid combination of auto-oxidation and hydrolysis as described in 5.1.3 and 5.1.4. The fast reaction leads to a change in dimension in the outer, exposed layer of the foam. This causes cracks, which allow moisture to penetrate the cell structure, where a second layer is then attacked, it cracks and allows further penetration. Although high temperatures on sandwich panels are described in this report, they occur on the face of a panel only. As PUR sandwich panels are, unlike mineral wool panels, more or less diffusion tight, it is very unlikely that high humidity levels are reached directly behind the face of a sandwich panel. Such scenarios, therefore, do not describe the in situ climate attack on a PUR sandwich panel core correctly. To the authors, knowledge problems in this respect were also not reported from practice.

5. All of the above mentioned factors may overlap or even influence each other.

The influence of some of the described effects can begin at some point after the ageing process has started. For illustration of the interaction of different factors it is assumed in figure 5-51 that the influence of three parameters is linear and parameters start influencing the test results at different time periods.

![Diagram](image)

**fig. 5-51** influence of different deterioration factors over time on tested strength parameter

The reduction of the initial low pressure for example is an effect that starts at the beginning of the panel lifetime and continues until external and internal pressure levels have equalized
completely. As has been illustrated before, such process can take more than a century. Depending on the oxygen content and thus on the evaluated location in the polymer matrix, the deterioration of the polymers can start (e.g. deterioration factor A). This means that for most areas the effect caused will be noticeable only with a time delay. It is a possible scenario that, depending on the amount of deterioration products available, a secondary polymerization can be initiated leading to an increase in strength (e.g. deterioration factor B). The new product may then itself be subject to oxidation and the breakdown may have even more influence on the mechanical strength of the foam (e.g. deterioration factor C). In reality the processes possibly run more complicated than illustrated here, but the illustration shows how overlapping effects influence each other and complicate the prediction of ageing influences on mechanical strength parameters.

5.5.9 Concluding remarks

It has been pointed out, that deterioration reactions, which lead to a decomposition of the polymeric structure in the cellular structure of PUR foams and, therefore, to a loss in mechanical strength, are likely to be caused by oxidation reactions initiated through oxygen that diffuses into the cellular matrix of the foam. These diffusion processes have been described mathematically and conversion tables, comparing the oxygen content in small scale samples at elevated temperatures with full scale samples under on site conditions, have been derived. Based on the results from the cross panel tensile testing, it can be discussed whether oxygen only is responsible for the deterioration of the polymers or not. It is, however, clear that the acceleration factor in the durability tests on small samples is determined through the geometric proportion between full scale panel and small scale sample, as well as the differences in exposure temperatures. The acceleration in the tests is not achieved through temperatures above the service limits like it is done in other field of application. When choosing a design dimension (width and length) of a sandwich panel for durability testing purposes, it is important to keep openings, such as windows and doors in mind. It is, in principle, no problem to perform a particular durability design for such cases by simply changing the assumed dimensions in chapter 5.5.2. Depending on the framing around a door or window, it may, in many cases, be assumed that the cut panel is sealed completely from air convection. It also needs to be balanced whether the principally necessary investigation justifies the expenditure on additional evaluation efforts or not.
The results from the small scale cross panel tensile tests show that deterioration in polymeric foam structures do not follow a predictable or mathematically describable function. Reason for this is that the time dependent development of the tested strength parameters are influenced by a variety of factors and that the obtained results are, therefore, difficult to describe and sometimes contradictory. For that reason it is important to choose an ageing scenario that embraces all possibilities of natural ageing. Based on the results presented here, ageing at 90°C for a total of 168 days, as required in prEN 14509, forms such an embracing ageing scenario at least with regards to oxygen diffusion. This can be vividly demonstrated by comparing the change in colour from fresh samples to aged samples as illustrated in figure 5-52.

Although the collected old panels tested in this research showed similar brownish colouring on the very outer layer, the inner part of the panels was always rather white. If this is accepted as an evidence for deterioration in the climate cabinet, having progressed further than in the real panel, then the proposed test covers the whole lifespan of a panel. It is then sufficient for a practical solution to disrupt the ageing process at intervals and to determine the remaining strength of the panel. Using the minimum of the found properties for design purposes, this will finally lead to a safe and practical design. The effect of humidity, which is ignored in this consideration, requires further research by chemical experts.
5.6 Synopsis on artificial ageing

Important sandwich panel core materials and their chemical background were presented in this chapter. Based on the gathered information, two ageing models were presented. One model, which was derived for mineral wool cores, is appropriate to core materials that are diffusion free. The other was derived for polyurethane cores and mirrors the situation for diffusion tight core materials. It is important to distinguish between these two major groups of materials, as they require completely different ageing scenarios. The presented results and the identified relationship between natural and accelerated ageing can only be seen as a first step towards a complete understanding of the deterioration in sandwich panels. There are certain weaknesses in the presented models that require further attention. For diffusion tight cores, such as polyurethane, these are:

1. The assumption that the deterioration of the mechanical properties is solely based on oxidation processes. Other factors also very likely contribute to the loss of mechanical strength. A more thorough investigation from chemical experts is required.
2. Even if the deterioration was solely dependant on the presence of oxygen, it remains unclear to what extent the concentration of oxygen is determining the reactions. It is unclear if small quantities of oxygen cause deterioration at the same speed as larger quantities do. Here also further investigations from chemical experts are required.
3. When looking at the diffusion models, the assumed diffusion constant has been determined for a particular foam. It is likely that the diffusion values vary with different foam core materials.

When looking at the diffusion free core materials (mineral wool), there are other uncertainties that should be considered in future research:

1. The implemented climatic recordings were based on data that was gathered in one single location over one single year only. As it is not possible to determine internal panel climates directly from external weather recordings, more information on internal sandwich climates in different regions should be gathered. This is particularly true for the humidity conditions inside the panel. Humidity variations, which play an equally important role as temperature variations, are difficult to predict and can vary immensely with local circumstances, such as geography or the surrounding development.
2. In his work Reentila makes rather radical assumptions when modelling the cross panel
tensile strength loss curves, which are the base for his model. Unfortunately, such
curves are often not really mathematically describable, as can be seen in, for example,
figure 5-19. The made assumptions influence the further developed model.

Despite all these assumptions, the models presented offer a base to approach the durability
problem in a reproducible manner. They allow assessing the acceleration factor samples in a
climate cabinet experience in relation to the natural ageing process. No bases for such an
assessment existed before this research. Future research will lead to improvement of the
models. The conducted research has shown that it is important to distinguish between ageing
models for diffusion tight core materials and core materials that are diffusion-free. The
important differences between the two ageing models are recapitulated in the following.

5.6.1 Diffusion free core materials

For diffusion free core materials, the total impact on a sandwich panel is condensed to a
relatively short time period in a climate cabinet. The conditions inside the cabinet and the
duration of the exposure time is based on climate recordings from the application site and
material specific properties that are derived from small scale cross panel tensile testing after
the exposure to a variety of climates. Such tests indicate the sensitivity of a core to moisture
and temperature, as well as the combination of both. As the samples are largely open to
diffusion, the climate effects all layers of the material. The dimension of the tested sample is
of no effect.

5.6.2 Diffusion tight core materials

In “diffusion tight” core materials, the shape of the sample, meaning its surface to volume
ratio, together with the exposure temperature determines the duration of an artificial ageing.
Here, it is rather the penetration of potential oxidation reaction partners, which determine the
advance of deterioration. Such penetration happens at interfaces between environment and
core material and is temperature dependent. The inner layers are, to a certain extent, protected
from external attacks.
6 Design consequences from deterioration of mechanical properties after artificial ageing

The previous chapter detailed the possibility to simulate natural ageing accelerated in a climate chamber. This chapter now identifies which tests actually need to be undertaken and explains how these should be evaluated. It has been highlighted in the introduction of this report that to solely evaluate the cross panel tensile strength through testing is insufficient for a quantity-driven determination of long term, durability implementing design factors. This chapter presents a test series, where all significant design factors affected by ageing were determined. A series of PUR core panels has been tested for all necessary design parameters connected to the sandwich core before and after ageing. The tests included:

1. Fresh samples: cross panel tensile test (strength and modulus), compressive test (strength and modulus), shear test (strength and modulus), six-point bending test, small scale wrinkling test (as presented in chapter 4.2)
2. Aged samples (7, 28, 56, 90 days at 90°C / <15% RH): cross panel tensile test (strength and modulus), compressive test (strength and modulus), shear test (strength and modulus), small scale wrinkling test

The results will now be used, to determine the actual performance of a sandwich panel after artificial ageing.

Following that, a theoretical approach to establish a mathematical relationship between important design parameters is presented. With the model derived albeit becomes possible to establish a relationship between cross panel tensile strength and wrinkling strength. It is also shown that, such the relationship between wrinkling and cross panel strength cannot be established without including the stiffness parameters of the core. The presented model implements a factor characterizing the pre-wrinkling deformation of a sandwich face when under compression. For the first time, such deformations have been evaluated in quantity in this research. The detection of pre-wrinkling deformations applied the latest three dimensional scanning methods.

The results obtained are then used to derive a durability implementing design approach. This includes durability factors for all important design parameters and is fairly simple for most design parameters except the wrinkling strength. The correction factor for wrinkling strength
is based, in particular, on durability implementing stiffness values of the core, as well as the durability implementing cross panel tensile test of the core.

In completion, an evaluation example based on the obtained test results is given and the obtained results are discussed.

6.1 Changes in design parameters

All important, core-related design parameters have been determined before and after ageing. In the following test, a series was undertaken on a separate set of pentane blown PUR panels. All specimens were taken from the same production batch, ensuring comparability of the obtained results. The panels investigated are, however, different from the samples used in the outdoor testing rig and for the exposure to various climate combinations. Thus their results cannot be compared directly with each other. For the determination of the initial strength and stiffness parameters, a total of 12 tests were performed. For the test series after ageing sets of five, specimen were tested after 7, 28, 56 and 90 days of exposure to a climate of 90°C and <15% RH. For evaluation, here again, the highest and lowest readings were eliminated and the average of the remaining results was determined. The results presented in the following are the mean values of three tests from one set of samples. Unlike in the graphs presented in chapter 5, it was chosen to present absolute values, as they are used further in the design process. A complete documentation of the tests can be found in chapter 9.

6.1.1 Compressive strength

Compressive strength after ageing can be determined through small scale testing. Samples, as described in chapter 4.1.2, have been tested in a small scale test after exposure to the artificial climate. Both, the ultimate compressive strength and the compressive modulus of the core, were determined. The development of the compressive strength over time is presented in figure 6-1.
After an initial drop determined at 7 days of exposure, the compressive strength seems to increase slightly over time. For a safe design, the minimum value obtained during the test cycle needs to be considered as a design value. The reason for the initial drop in performance may be any of the factors presented in chapter 5.5.8. For the compression strength, it seems, however, most plausible that partial low pressure, directly present after the production process and increased by rapid escape of carbon dioxide from the cell matrix, is responsible for the loss in performance. The sample then gains performance with the low pressure equalizing. The strength, even exceeding the initial parameter, can be explained because not only the low pressure caused by the escaping carbon dioxide but also the low pressure from the production process is equalized. The results obtained from the tests on the “old” panels presented in chapter 4.4 support this assumption. Here again, the compressive strength, found in the old panels, is rather higher than expected for a fresh panel. Similar effects have been observed by Friederichs (1998), who investigated the time dependency of compressive strength parameters on PUR insulation foams to study the effect of gas diffusion on dimension stability.
At the same time, the compressive E-modulus (see fig. 6-2) of the core remains almost constant. This again corresponds with the results obtained from the "old" panels collected, where the compressive modulus stays within the expected range (see chapter 4.5). In the design process for fresh samples, this parameter is not needed. It is, therefore, not necessary to determine a post-ageing design value. The value is, however, important for the mathematical evaluation of the wrinkling stress and, therefore, needs to be determined for a durability covering design approach.

### 6.1.2 Short Term Shear strength

Post-ageing shear strength has also been determined through small scale testing (see chapter 4.1.3). Shear samples are bigger than the samples in tensile and compression tests but fit into most climate cabinets. Again, a set of samples was tested after 7, 28, 56 and 90 days of exposure. For the PUR foams subject to this test series, the average shear strength developed as illustrated in figure 6-3.
Here again, no dramatic changes are observed. Once more, this is in compliance with the results found in the "old" sandwich panels. For a design, the minimum value should be used again. In the test series, presented here, this minimum was reached after 56 days of ageing. The development of corresponding shear modulus is presented in figure 6-4.
The changes here are, once more, not dramatic, but clearly visible. The results are in consonance with the results obtained from the “old” panels. The lowest value is reached after 56 days of ageing. As the parameter is important in sandwich panel design, when determining load deflections, it is necessary to determine a design value after ageing.

6.1.3 Tensile strength

As mentioned before, the cross panel tensile test is not a value needed for design. It is, however, a parameter giving information on panel integrity and is, therefore, mandatory for production control, as well as a stated value on the CE label of a sandwich panel. For the samples tested here, the tensile strength development over time was determined as presented in chapter 4.1.1. The obtained results are illustrated in figure 6-5.

![Tensile strength graph](image)

**fig. 6-5** development of tensile strength in PUR core over time after ageing at 90°C and < 15 % RH. Samples were tested after 0, 7, 28, 56 and 90 days.

A relatively sharp loss in strength at the beginning was observed. When compared to other results from similar ageing tests (see chapter 5.5.8), this can almost be considered as a typical behaviour. It is observed very often that, after a certain decrease in strength, the samples gain performance and somewhat higher tensile strength can be achieved. This can then drop again after prolonged exposure times. The reasons for this somewhat unpredictable behaviour have been identified in chapter 5.5.8. Walter and Wendel (1992) investigated the development of
internal pressure in PUR foam cells. They found that the pressure inside the cells can drop to 0.7 atm. The low pressure needs to be added to the tensile strength of the sample:

\[ 1.0 \text{ atm} - 0.7 \text{ atm} = 0.3 \text{ atm} = 0.3 \times 10^3 \text{ kPa} = 0.03 \text{ N/mm}^2 \]

Such a change in internal pressure can at least, to some extent, be held responsible for these unpredictable changes. This is particularly true as the effects overlap. Although the tensile strength is not a direct design parameter, it is an important parameter determining the wrinkling strength of a panel, as will be discussed in detail at a later stage (see chapter 6.2). The same is true for the tensile E-modulus which is presented in figure 6-6.

\[
\begin{align*}
\text{absolute Tensile Modulus (development at 90°C)}
\end{align*}
\]

fig. 6-6 development of tensile E-modulus in PUR core over time after ageing at 90°C and < 15 % RH. Samples were tested after 0, 7, 28, 56 and 90 days.

The tensile modulus is not directly needed for sandwich panel design but plays a role when finding a connection between tensile strength and wrinkling strength of a panel.

With the cross panel tensile test, once more, a principle tendency is mirrored in the results obtained from the “old” sandwich panels. The cross panel tensile strength was found to be rather low compared to the expected results. At the same time, the corresponding stiffness parameter stayed unaffected.
6.1.4 Wrinkling strength

The wrinkling strength on aged samples was determined, making use of the small scale test presented in chapter 4.2. No pre-wrinkling deformation, except the "natural" deformation which occurs during production, was used on the samples tested after exposure. The initial strength values were determined, using the six point bending test as described in chapter 4.1.4, as well as with the help of the small scale wrinkling test with and without the additional load device, which simulated the deformation under the load introductory areas in the full scale test. Aged samples were tested after 7, 28, 56 and 90 days of exposure. The results are presented in figure 6-7.

![Diagram showing wrinkling strength development](image)

The presented results show that the small scale wrinkling test on fresh samples without load device (228.7 N/mm²) shows a good correlation with the theoretical wrinkling strength when determined as will be presented in equation 6.2-23 in chapter 6.2 (224.5 N/mm²). At the same time, the small scale wrinkling test with the additional load device (178.8 N/mm²), which causes a load dependent deformation of the panel face, gives almost the same results as the full scale six point bending test (180.9 N/mm²).

The changes in wrinkling strength over the ageing process are not dramatic, but noticeable. When comparing the highest and lowest mean value found, a drop of 19.87 % was observed. Compared to the initial value, the biggest drop was 19.83 %. For a safe design process, it is once more necessary to calculate against the lowest wrinkling strength found.
Just like in the small scale specimen from the cross panel tensile and compression tests and as illustrated in figure 5-51, the bone shaped samples in the small scale wrinkling tests have changes their colour.

Figure 6-8 shows the change of colour in the PUR foam. The creamy white from un-aged samples turns to brownish after 90 days at 90°C. The brown colour is a clear sign for oxidation reactions in PUR polymers.

6.1.5 Concluding remarks on post ageing tests

The tests presented above allow a determination of design values for all necessary material properties, respecting also ageing effects. The test programme is, however, intense and cost-intensive. For an easier test programme, it is desirable to exclude at least the small scale wrinkling test from the programme. It is, therefore, necessary to predict the change in wrinkling strength based on the outcome of the other small scale tests.
6.2 Establishment of mathematical connection between wrinkling and tension capacity

The strength of the compressed face of a sandwich panel may be limited either through yielding of the face material or, as is found more frequently in real structures, a short wave length buckling failure where the sandwich faces reaches the so called “wrinkling strength”. Wrinkling is a sudden localised buckling of the compressed sandwich panel face, which is stabilized by the rigid core. The allowable compression strength of a face is then determined by its thickness, its geometry and the strength and stiffness of the core. In the following in particular thin flat faces are concerned. It has been shown in chapter 4.2, when the newly developed small scale wrinkling test was discussed, that the bending moment in a three layer sandwich structure, is resisted by axial stresses in the faces. The structure is then often compared to an I-beam, where the sandwich faces represent the beam flanges. Unlike an I-beam however, the sandwich panel is a plain structure where the core provides certain bedding for the faces. The quality of such bedding is determined through the stiffness of the core as well as its strength parameters. It is obvious, that a thin metal face on its own would fail immediately through buckling when under compression. The form of buckling would correspond to the respective Euler case and depend on the support situation. Only with the constant bedding of the core can the critical wave length be reduced and the buckling failure is increased. The length of a buckling wave is, then again, determined through the supporting conditions but this time the support is provided over the whole length of the structural member under compression, which is the face.

When only looking at a finite part of this compressed face and based on previous work by Plantema (1966) and Linke (1978), a model, describing the wrinkling conditions by taking the initial deformation of the sandwich face into consideration, can be written as

\[ D \cdot \frac{\partial^4 (w - w_0)}{\partial x^4} + c \cdot (w - w_0) = -\sigma_x \cdot t \cdot \frac{\partial^2 w}{\partial x^2} \]

\[ \text{eq. 6.2-1} \]

The geometric conditions are illustrated in figure 6-9.
Assuming the initial deformation as a sinusoidal wave, where the wave length corresponds to the first eigenvalue of the stability problem, the deformation of the face can be written as follows.

\[ w - w_0 = (f - f_0) \cdot \sin \frac{\pi \cdot x}{a} \]

where

- \( a \): length of sine curve half wave

Proceeding on the assumption that the deformation of the supporting core can be described as an elastic half-space where
where

\[ k: \text{ decay index} \]

With

\[ \text{eq. 6.2-4} \quad \sigma_z = E_e \cdot \varepsilon = E_e \cdot \frac{\partial \nu}{\partial z} \]

and

\[ \text{eq. 6.2-5} \quad \tau_{zz} = G_e \cdot \gamma_{zz} = G_e \cdot \frac{\partial \nu}{\partial x} \]

and making use of the previously made assumptions for the deformation, the stresses in the core can be computed as

\[ \text{eq. 6.2-6} \quad \sigma_z = -E_e \cdot k \cdot (f - f_0) \cdot \sin \frac{\pi \cdot x}{a} \cdot e^{-kz} \]

\[ \text{eq. 6.2-7} \quad \tau_{zz} = G_e \cdot \frac{\pi}{a} \cdot (f - f_0) \cdot \cos \frac{\pi \cdot x}{a} \cdot e^{-kz} \]

The internal potential energy of the core can be derived from

\[ \text{eq. 6.2-8} \quad \pi_i^e = 0.5 \cdot \left[ \int_{0}^{a} \int_{0}^{a} \frac{\sigma_z^2 + \tau_{zz}^2}{E_e + \frac{G_e}{G_e}} \, dx \, dz \right] \]

In combination with equation 6.2-6 and equation 6.2-7 the potential can be written as

\[ \text{eq. 6.2-9} \quad \pi_i^e = \frac{E_e \cdot k}{8} \cdot (f - f_0)^2 \cdot \alpha + \frac{G_e \cdot \pi^2}{8 \cdot k \cdot \alpha} \cdot (f - f_0)^2 \]

The decaying index can be derived from the minimum of the internal potential
which solves to

\[
eq 6.2-11 \quad k = \frac{\pi}{a} \sqrt{\frac{G_c}{E_e}}
\]

The decaying index can now be employed in equation 6.2-9 which leads to

\[
eq 6.2-12 \quad \pi_i^e = \frac{\pi}{4} (f - f_0)^2 \cdot \sqrt{G_c \cdot E_e}
\]

Comparing the internal potential of the core and the potential of constant bedding, the bedding stiffness can be obtained, from

\[
eq 6.2-13 \quad \pi_i^b = \int_0^w c \cdot (w - w_0) \, dw \, dx = \frac{c}{4} \cdot (f - f_0)^2 \cdot a
\]

\[
\pi_i^b = \pi_i^e
\]

\[
c = \frac{\pi}{a} \cdot \sqrt{E_e \cdot G_e}
\]

by making use of equation 6.2-2, this leads to

\[
eq 6.2-14 \quad D \cdot \frac{\pi^4}{a^4} \cdot (f - f_0) \cdot \sin \frac{\pi \cdot x}{a} + \frac{\pi}{a} \cdot \sqrt{E_e \cdot G_e} \cdot (f - f_0) \cdot \sin \frac{\pi \cdot x}{a} = -n_x \cdot f \cdot \frac{\pi^2}{a^3} \cdot \sin \frac{\pi \cdot x}{a}
\]

where

\[
n_x: \ \text{force per unit width} \quad n_x = \sigma_x \cdot t
\]

The plain force per unit width results to

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The critical half wave length can be calculated from

\[ \frac{\partial n_x}{\partial a} = 0 \]

resulting in

\[ a = \pi \sqrt[3]{\frac{2 \cdot D}{E_o \cdot G_o}} \]

This again, together with equation 6.2-15, results in

\[ n_x = \frac{f - f_0}{f} \cdot 1.8899 \cdot \sqrt[3]{D \cdot E_o \cdot G_o} \]

The wrinkling capacity \( (n_x^w) \) derives from

\[ \frac{\partial n_x}{\partial f} = 0 \]

which leads to \( n_x^w \) for \( f \to \infty \)

\[ n_x^w = 1.8899 \cdot \sqrt[3]{D \cdot E_o \cdot G_o} \]

From equation 6.2-17 and equation 6.2-18, the deflection of the finite element can be written as

\[ w = w_0 + f_0 \cdot \left( \frac{n_x^w}{n_x^w - n_x} - 1 \right) \sin \frac{\pi \cdot x}{a} \]
From $M = -E \cdot I \cdot (w - w_0)$ the maximum bending moment in the face can be derived and shown to be

$$\text{eq. 6.2-20} \quad \max M = \frac{\pi^2}{\alpha^2} \cdot D \cdot f_0 \cdot \frac{n_x}{n_x^w - n_x}$$

Since $\sigma_e = c \cdot (w - w_0)$, the maximum core stress perpendicular to the face results in

$$\text{eq. 6.2-21} \quad \max \sigma_e = \frac{\pi}{a} \cdot \sqrt{E_c \cdot G_c} \cdot f_0 \cdot \frac{n_x}{n_x^w - n_x}$$

where

$$n_x = \sigma_x \cdot A(t)$$
$$n_x^w = \sigma_x^w \cdot A(t)$$

Applying the face stiffness ($D$) to equation 6.2-18 and assuming $\mu = 0.3$, the buckling strength can be written as

$$\text{eq. 6.2-22} \quad \sigma_{\text{ml}} = 0.851 \cdot \sqrt{E_c \cdot G_c}$$

According to Linke (1978), it has been found that for many material combinations the ultimate wrinkling strength ($\sigma_u^w$) found in testing is

$$\text{eq. 6.2-23} \quad \sigma_u^w = 0.6 \cdot \sigma_{\text{ml}}$$

The necessity of such a factor, however, shows the discrepancy between the theoretical approach and experimental findings. When undertaking a full scale bending test, the setup is mostly a single span test with four equal line loads, as has been described previously (see fig. 4-8). The line loads represent an area load but are unfavourable as they cause local deformations at the points of loading. These imperfections result in lower wrinkling strength values than found in theory or in some vacuum chamber bending tests, where the load is really applied on the whole area.
For the purpose of this work, however, the model is sufficiently accurate and establishes the connection between wrinkling and tension capacities, as well as between wrinkling capacity and other material factors such as elastic modulus and shear modulus.

Considering equation 6.2-21 and equation 6.2-22, it becomes obvious that the most important factors affecting the wrinkling strength of a sandwich panel are:

- Elastic modulus of the core (\(E_c\))
- Shear modulus for the core (\(G_c\))
- Elastic modulus of the face (\(E_f\))
- Tension capacity of core (core-core / core-face) (\(f_c\))
- Initial deformation of the face (\(a\) and \(f_0\)) (pre-wrinkling deformation)

The elastic modulus of the core is generally taken as the average of tension and compression module.

\[
eq. 6.2-24 \quad E_c = \frac{E_{ct} + E_{ct}}{2}
\]

For common panel cores, the elastic modulus (\(E_c\)) generally lies between 1 and 20 N/mm\(^2\). Approximately the same range is true of the shear modulus. As this work focuses on sandwich panels with thin steel faces, the elastic modulus for the face (\(E_f\)) can be kept at 210,000 N/mm\(^2\). The initial deformation (\(f_0\) and \(a\)) of the surface is a determining factor which needs close attention. In the following such deformations are investigated in further detail.

6.2.1 Pre-wrinkling deformation of flat sandwich panel face

Up to now, pre-wrinkling deformation has only been estimated, lacking scientific information on the shape of the deformation and its depth. Equation 6.2-2 assumes that the deformation of the face under plain stress is of sinusoidal shape. The critical wave length is mathematically derived in equation 6.2-16. The maximum deformation is in accordance with Linke (1978), who refers to Plantema (1966), assumed to be

\[
eq. 6.2-25 \quad f_0 = \frac{a}{500} \quad \text{with} \quad a = \pi \cdot \sqrt{\frac{2 \cdot D}{\sqrt{E_c \cdot G_c}}}
\]
Here, the divisor 500 is based on assumptions (empirically on test results). At the same time, the influence of this factor on the wrinkling strength is linear (see eq. 6.2-21), giving the factor a considerable influence on the overall result. Further investigation of the pre-wrinkling deformation of in plain stressed sandwich faces is described in the following.

Latest surveying technology makes accurate surface assessment possible. The pre-wrinkling deformation of sandwich panels with flat or lightly profiled surfaces was investigated, employing a GOM ATOS II 3dscanner by Schlüter, Pfeiffer et al. in 2004. The employed scanner is able to work in the sub millimetre range while surveying an area of approximately 1000 mm x 1000 mm. Sandwich panels with EPS core and metal faces were investigated in this research. The accurate deformation of the face was recorded periodically in both, full scale bending tests and small scale wrinkling tests. Furthermore, the accurate mechanical panel parameters were tested. Employing the obtained results for elastic modulus of the core, shear modulus of the core and stiffness of the lightly profiled face into equation 6.2-25 lead to an expected wavelength of $\lambda = 78.8$ mm and an amplitude of $h_0 = 0.16$ mm for the investigated panels. For the investigation, a six point bending test setup, as described in chapter 4.1.4, was chosen together with the small scale wrinkling test as described in chapter 4.2. The surveying equipment was focused on the area of maximum in plain stress of the panel face (see fig. 4-4).

![test setup with GOM ATOS II scanner and small scale sample (left); six point bending test with loading at quarter points and the detected area in the middle (middle); failed sandwich panel (right)](image)

The use of two different testing machineries, one testing with the specimen in vertical direction and one testing in horizontal direction, as well as the varying size of the detected area, required the employment of a portable 3d scanning system. The photogrammetric GOM
ATOS II 3d scanner, which employs stripe projection, has the necessary flexibility in test setup and a sufficient resolution in the sub millimetre range (Böhler and Marbs, 2002). One surface scan with this system requires 15 to 20 seconds. The load in the test setup was increased in increments, allowing 10 to 12 scans before wrinkling failure of the sandwich structure. The duration of one test was, therefore, between 15 and 20 minutes. For this experiment the absolute movement of the sandwich panel (bending deflection) is unimportant. The reference area is, therefore, marked with retro targets directly on the surface of the panel. Because of this, the evaluating software interprets movements of the surveyed object into movements of the sensor. This effect has been evaluated and checked in advance on a reference surface and could be confirmed. The scanned 3d points were meshed as triangles and then transferred to a digital 2.5 dimensional image with a greyscale colour depth of 4 byte per pixel. In order to get a more accurate picture of the true movement of the face, picture differences for different load increments were subtracted. The result is a picture of the differences between individual load increments, which is then again subject to frequency analysis. The remaining deformation can now be separated in a low frequency part, resulting from the bending deflection of the whole panel and the high frequency short wave pre-wrinkling deformation of the face.

Good correlation has been found for the wavelength. In principle, this is also true for the amplitude, though with some restrictions. The amplitude is often subject to local disturbance (see fig. 6-11 where black colour marks the areas of large deformation). This can explain the,
practical requirement for the factorization of the theoretical wrinkling strength, which is implemented in equation 6.2-23. For further consideration, the assumptions made in equation 6.2-25 and equation 6.2-2 are considered as a reasonable model of the real panel.

6.2.2 Bedding stress on panel core

The cross panel tensile test has previously been identified as one of the determining factors for the wrinkling strength. The actual stress on the panel core is dependent on the actual in plane stress on the faces in relation to the ideal wrinkling strength and the deformation of the face. This was described in equation 6.2-21 and is repeated in the following.

\[
\max \sigma_c = \pi \cdot \sqrt{E_c \cdot G_c \cdot f_0} \cdot \frac{n_x}{n_x^{\text{in}} - n_x}
\]

for a typical panel with a unit width and a face thickness of \(t_f\), the equation develops to

\[
\text{eq. 6.2-26} \quad \max \sigma_c = \frac{\pi}{a} \cdot \sqrt{E_c \cdot G_c \cdot f_0} \cdot \frac{\sigma_x \cdot t_f}{\sigma_x^{\text{in}} \cdot t_f - \sigma_x \cdot t_f}
\]

The latter fraction of the equation describes the ratio between actual in plane stress and maximum in plane stress, which is the ideal wrinkling strength of the panel. Equation 6.2-26 indicates that the bedding stress on a sandwich core is not only dependent on the in plane stress to ideal wrinkling stress ratio, but also on the product of elastic modulus of the core and shear modulus of the core \((E_cG_c)\). As mentioned before and demonstrated in equation 6.2-25, this product also influences the pre-wrinkling deformation. Assuming that the stiffness of the face itself stays unaffected, which can always be assumed for durability evaluation, the dependencies established in equation 6.2-26 can be plotted in a three dimensional manner.
fig. 6-12 three dimensional view on relationship between stiffness of the core, tensile strength of the core and exploitation of wrinkling strength

For the practical range which is for the stiffness of a sandwich panel between

\[ E_e \cdot G_c = 1 \quad \rightarrow \quad E_e \cdot G_c = 100 \, N^2 / mm^4, \]

the graph can also be plotted in a two dimensional manner with the corresponding boundary lines.
The graph indicates that the core must provide a certain bedding strength to activate the wrinkling capacity of the face. In principle and as illustrated below (see fig. 6-14), the core is stressed with both, compression ($-\sigma_c$) and tension ($+\sigma_c$) stresses.

For further considerations, it is, however, assumed that the cross panel tensile strength is the determining factor in face bedding. The reason why tensile strength is more critical and, therefore, in practice mostly the decisive factor is that, in many cases, the ultimate compressive strength is defined by limitation in core deformation (see chapter 4.1.2). This, however, does not mean that the core suddenly fails in compression, as is true for the cross panel tensile strength, but still provides adequate bedding for the face. Nevertheless, there may be cases where the compressive strength is the decisive factor. The wrinkling strength of
a sandwich panel can, on all accounts, be reduced to an excess of the bedding strength of the core.

The required bedding strength of the core depends on the stiffness of the core. A relatively "poor" core material with low bedding stiffness (i.e. red line in fig. 6-13, stiffness product $E_c G_c = 1 \text{ N}^2/\text{mm}^2$) requires a relatively low bedding strength to activate a wrinkling strength, which is close to its ideal wrinkling strength. For a "good" (i.e. blue line in fig. 6-13, stiffness product $E_c G_c = 100 \text{ N}^2/\text{mm}^2$) core with relatively high stiffness, as for example a mineral wool core panel, the required strength is considerably higher. It is important to keep in mind that the axis of ordinates in figure 6-13 represents the ratio between actual in plane stress and ideal wrinkling strength. For a high stiffness core, the absolute value is considerably higher than for a low stiffness core. With respect to durability and in particular to a potential loss in cross panel tensile strength, this means that it is important to include the panel core stiffness into the durability considerations. If, for example, a sandwich panel with a core stiffness, following the red line in figure 6-13, found to have an initial cross panel tensile strength of 0.3 N/mm² and then loses 50% of its strength due to durability reasons, the influence on the wrinkling strength can be neglected. Had the same panel been found to have an initial cross panel tensile strength of only 0.05 N/mm², which would have had a minor influence on the initial wrinkling strength, a loss of 50% in cross panel strength would have dramatic effects for the wrinkling strength. It becomes clear that the cross panel tensile strength cannot be looked at individually when determining the impact of durability on the overall panel performance. It is rather the interaction between core stiffness and cross panel tensile strength that determines the impact durability related degradation has on the overall panel performance.

Knowing that the principal parameters influencing wrinkling strength are:

- mean value of tensile and compression E-modulus
- shear modulus
- tensile strength of core,

it is now possible to propose a full durability evaluation scheme on the basis of small scale tests without need for a small scale wrinkling test.
6.3 Full testing evaluation for assessment of sandwich panel durability

Based on all factors presented in the previous chapters, it is possible to propose a full testing scenario which can help to estimate the long term mechanical behaviour of a sandwich panel. In a first step, it is important to ascertain whether the core material of the panel can be considered as diffusion tight or as diffusion free. Depending on the outcome, either a test combining temperature and humidity, as presented in chapter 5.4, or a test at elevated temperature, as presented in chapter 5.5, must be chosen. The two tests procedures can currently only be proposed for use with PUR and mineral wool cores, as they have only been evaluated using these materials and some factors may be material specific. However, it is likely that other rigid plastic core materials, such as phenolic foams, are expected to behave comparably with PUR foams. Nevertheless, more testing is required in this area.

With the knowledge available at the moment, it is important that the following small scale durability tests on a sufficient number of specimens are carried out:

- Cross panel tensile test determining tensile strength and E-modulus
- Cross panel compression test determining compressive strength and E-modulus
- Shear test determining shear strength and shear modulus

The tests need to be carried out after a sufficient number of time intervals. The intervals chosen here are 7, 28, 56 and 90 days. Depending on the choice of test condition (exposure temperature and humidity) and expected length of product life cycle, longer or shorter intervals may be required and can be determined on the base of the findings presented in chapter 5. A total of four time intervals, dividing the total period as in the presented 90 days scenario (see chapter 4.3), is probably consistent, though a smaller number of time segments is required in prEN 14509. It is however the aim of dividing the total testing period into time intervals, to find the lowest strength value occurring during the lifetime of a panel. Thus, a larger number of intervals increases the possibility to find this minimum value. At the same time, it is impractical to conduct a countless amount of tests. Further investigation to this subject is needed and should be future work for chemical experts trying to get a better understanding of the possible deterioration reactions. For the time being the chosen test intervals are assumed as sufficient for further considerations.
The minimum value found shall be employed for determination of the reduction factor. A problem occurs when determining the average value of each property tested. Durability testing is expensive and time consuming. It would, therefore, be favourable to determine the durability property of a particular foam system only once. A general reduction factor can then be introduced which is applied to values determined from testing on “fresh” samples, which is done regularly. When determining characteristic design values, it is necessary to take the scatter of test results into account and determine the fractile value. By reducing fractile values (tests on fresh samples) on the base of results from average values (aged samples), it is assumed that the scatter for both sets of test results is equal. Such an assumption is mathematically incorrect but is proposed at this point for practicality. The effect can be assumed as minimal, as a variation in test results is largely based on inhomogeneity of the tested material and test setup. These factors are very much alike for the compared test series.

The durability correction factors for the relevant properties after a time period, chosen through a certain test duration and artificial climate, are now simply determined by comparing the lowest value obtained in durability tests with the initial strength and stiffness values. For the cross panel tensile strength of the core, the durability correction factor is determined by:

\[ k_{ctf} = \frac{f_{ctd}}{f_{ct}} \]

where

\[ k_{ctf} \]: correction factor for durability of tensile strength of core \((k_{ctf} \leq 1)\)
\[ f_{ctd} \]: lowest average tensile strength found in aged samples
\[ f_{ct} \]: average tensile strength found in new samples

When looking at the corresponding correction factor for the stiffness values, this is given by:

\[ k_{ctE} = \frac{E_{ctd}}{E_{ct}} \]

where

\[ k_{ctE} \]: correction factor for durability of tensile E-modulus of core \((k_{ctE} \leq 1)\)
\[ E_{ctd} \]: lowest average tensile E-modulus found in aged samples
\[ E_{ct} \]: average tensile E-modulus found in new samples
The characteristic design factors including durability correction factors are then determined through, for example,

\[ f_{c,ck} = k_{C_E} \cdot f_{c,5\%} \]

where

- \( f_{c,ck} \): characteristic design value for tensile strength
- \( k_{C_E} \): correction factor for durability of tensile strength of core \((k_{C_E} \leq 1)\)
- \( f_{c,5\%} \): 5% fractile value for tensile strength determined on unaged (new) samples

All other characteristic parameters (tensile modulus; compressive strength and modulus; shear strength and modulus) can be determined accordingly giving durability correction factors \((k_{C_E}, k_{C_S}, k_{C,06}, k_{C,05}, \text{ and } k_{C,0})\). For the wrinkling strength a slightly more complicated approach needs to be taken.

Based on the outcome of the proposed durability testing, it is now possible to adjust all important design parameters. This is particularly important for the wrinkling strength. As presented in chapter 6.2., the wrinkling strength of a panel is dependent on the above introduced durability considering:

- shear modulus of the core
- tensile E-modulus of the core
- compressive E-modulus of the core
- tensile strength of core
- deformation of the face

With the results obtained from the testing scenario presented in chapter 6.3 and using equation 6.2-21, it is now possible to predict also the wrinkling strength after ageing. In a first step, the tensile strength is assumed to have no impact on the wrinkling strength after ageing. The durability implementing wrinkling strength can then be determined by utilizing a normalization equation which is in accordance with prEN 14509:

\[ k_{d_1} = \sqrt[3]{\frac{E_{cd} \cdot G_{cd}}{E_c \cdot G_c}} \]
where

- k\text{DL}: correction factor for long term wrinkling strength of panel including durability
- E\text{C}: average of E-modulus of the core in compression and tension determined through testing in accordance with prEN 14 509
- G\text{C}: shear modulus of the core determined through testing in accordance with prEN 14 509
- E\text{CD}: average of E-modulus of the core in compression and tension including durability factor
- G\text{CD}: shear modulus of the core including durability factor

For an accurate design, it is in any case necessary to also take the change in tensile strength into account. This can be done by comparing theoretical reductions in wrinkling strength caused by loss in tensile strength, which is evaluated through testing and applying the determined ageing factors to the strength values found in full scale testing. As a base for such evaluation, it is necessary to reconsider equation 6.2-26:

\[
\max \sigma_e = \frac{\pi \cdot a \cdot \sqrt{E_c \cdot G_c \cdot f_0}}{\sigma_{\text{ef}}^* \cdot t_f} \cdot \frac{\sigma \cdot t_f}{\sigma_{\text{ef}}^* \cdot t_f - \sigma \cdot t_f}
\]

The equation can be solved against expected wrinkling strength which leads to:

\[
\text{eq. 6.3-5} \quad \sigma_e = \frac{\sigma_{\text{wl}}}{1 + \frac{\pi \cdot a \cdot \sqrt{E_c \cdot G_c \cdot f_0}}{\sigma_{\text{ef}}^* \cdot t_f}} \cdot \frac{1}{f_{ca}}
\]

For the aged sample this equation changes to

\[
\text{eq. 6.3-6} \quad \sigma_{\text{wlD}} = \frac{\sigma_{\text{wlD}}}{1 + \frac{\pi \cdot a_\text{D} \cdot \sqrt{E_{\text{CD}} \cdot G_{\text{CD}} \cdot f_{\text{CD}}}}{\sigma_{\text{wl}} \cdot \sigma_{\text{CD}} \cdot f_{\text{CD}}}} \cdot \frac{1}{f_{\text{CD}}}
\]

where

- \sigma_{\text{wlD}}: ideal wrinkling strength of aged panel (\sigma_{\text{wlD}} = 0.85 \cdot \sqrt{E_f \cdot E_{\text{CD}} \cdot G_{\text{CD}}})
- a_D: length of the sinusoidal half wave in aged panel (a_D = \pi \cdot \sqrt{\frac{2 \cdot D}{E_{\text{CD}} \cdot G_{\text{CD}}}})

- \sigma_{\text{wl}}: wrinkling strength of panel
- \sigma_{\text{CD}}: durability factor
- \sigma_{\text{ef}}^*: effective tensile strength
- \sigma_{\text{ef}}^*: effective tensile strength
- f_0: initial tensile strength
- f_{ca}: compressive strength
- f_{\text{CD}}: compressive strength
- E_{\text{CD}}: compressive modulus
- G_{\text{CD}}: shear modulus
- D: characteristic size of the panel

- a: characteristic length of the panel
- \pi: mathematical constant
- \sqrt{X}: square root of X
A comparison of the expected wrinkling strength before and after ageing now allows the determination of a correction factor for wrinkling strength.

The second correction factor for durability including changes in core stiffness and also changes in tensile strength ($k_{D2}$) can now be introduced:

$$k_{D2} = \frac{\sigma_{wD}}{\sigma_w}$$

In combination with equation 6.3-5 and equation 6.3-7 this can be written as

$$k_{D2} = \frac{1+\frac{\pi}{a} \sqrt{E_c \cdot G_c \cdot f_0 \cdot \frac{1}{f_{cD}}}}{1+\frac{\pi}{a_D} \sqrt{E_{CD} \cdot G_{CD} \cdot f_{0D} \cdot \frac{1}{f_{CD}}}} \cdot \frac{\sigma_{wD}}{\sigma_{wi}}$$

where

- $a$: length of sine curve half wave
- $G_c$: shear modulus of core
- $E_c$: Young's modulus of core
- $f_0$: initial deformation of the face
- $\sigma_{wi}$: buckling strength of face

All factors may also carry the subscript $D$ meaning the above mentioned value, but implementing a durability factor.

Equation 6.3-8 can now be applied to the results obtained in chapter 6.1. The result is the theoretical change in wrinkling stress. The obtained properties can then be related to the results from the small scale wrinkling tests. Figure 6-15 illustrates the outcome. The individual test results together with the observed failure modes are summarized and presented in chapter 9.
A good correlation between the theoretically expected loss in strength and the strength values determined through the small scale wrinkling test is found.

Looking at equation 6.3-8 more generally, it becomes clear that the influence of changing stiffness and cross panel tensile strength on wrinkling strength is complex. Not only does the influence depend on the ratio between pre- and post ageing \((k_{cE}, k_{cC}, k_{CG}, \text{ and } k_{Cf})\), it also depends on the absolute values, respectively the product of the initial stiffness values \((E_c, G_c)\) and the initial cross panel tensile strength \((f_{Ct})\). The problem, therefore, cannot be illustrated in a three dimensional graph. By choosing an initial value for either the stiffness of the core (product of \(E_c, G_c\)) or the initial cross panel tensile strength \((f_{Ct})\), the problem can be reduced to the three dimensional dependency. For an initial cross panel tensile strength of 0.1 N/mm² the development of \(k_{D2}\), the correction factor for the wrinkling strength is illustrated in figure 6-16. Four different stiffness products are plotted. The field of experience for today’s sandwich core materials is roughly between 10 and 100 N/mm². The rather extreme values of 1 and 1000 N/mm² are plotted to visualize the principle behaviour of the dependency.
If the stiffness product is now kept at a constant 100 N/mm$^2$ and the cross panel tensile strength is varied, the correction factor for the wrinkling strength develops as illustrated in figure 6-17. The expected range in cross panel tensile strength for sandwich panels is currently somewhere between 0.05 and 0.5 N/mm$^2$. However, new materials entering the sandwich market may soon enlarge that range considerably.
6.4 Discussion of results

The presented way of taking deterioration of mechanical properties into account is, with the exception of wrinkling strength, straightforward. Simply ageing samples and testing the relevant mechanical properties can only be a first step to durability implemented design. However, it is the only safe approach to take at the moment. Future research will show if adequate correlation between individual mechanical material properties and their change over time can be found. Current research in Mainz (Kurpiela 2005) shows that, for un-aged sandwich panel core materials, it is possible to find a correlation between individual material properties. So far, the density was in most cases taken as an indicator for expected properties. The new model determines links between mechanical strength and stiffness parameters. This is also necessary for a durability-related consideration as deterioration in mechanical strength does not come with deterioration or loss in material density. It will, however, be necessary to
verify such a model for ageing related deterioration. Extensive research is planned in this field for the future. This will include determination of compressive and shear strength, as well as the associated elastic moduli. The proposed small scale wrinkling test here offers a good opportunity to gather more results of the effect of these properties on wrinkling strength, which would help to prove the mathematical determination of the ageing effect on wrinkling.

The proposed procedure for taking changes in stiffness and strength parameters into account, when determining the influence on wrinkling strength, can be adopted for other fields of application. Currently, German approval authorities, for example, accept to account for changes in core stiffness, which may, for example, occur when changing foam systems in production, through comparison of ideal wrinkling strength. The correction factor then is, as illustrated in equation 6.3-8:

\[
k_{D1} = \sqrt[3]{\frac{E_{CD} \cdot G_{CD}}{E_C \cdot G_C}}
\]

In principle, the same equation is used in chapter A.5.5.5 of prEN 14 509 for the determination of wrinkling strengths at elevated temperatures:

\[
eq 6.4-1 \quad k_1 = \frac{E_{C_{1,>20^\circ C}}}{E_{C_{1,>20^\circ C}}}
\]

For this equation, it is assumed that the change in shear modulus at elevated temperature is the same as determined for the elastic modulus.

Going back to equation 6.3-12 (see below), the relationship between ideal and actual wrinkling strengths is found in the latter factor:

\[
k_{D2} = \left( \frac{1 + \frac{\pi}{a} \cdot \sqrt{E_C \cdot G_C \cdot f_0 \cdot \frac{1}{f_{C1}}}}{1 + \frac{\pi}{a_D} \cdot \sqrt{E_{CD} \cdot G_{CD} \cdot f_0 \cdot \frac{1}{f_{CD}}}} \right) \left( \frac{\sigma_{w1D}}{\sigma_{w1}} \right)
\]
The influence of the first factor on the correction factor, when neglecting the changes in cross panel tensile strength \( (f_c = f_{cd}) \) and the changes in the deformation of the face \( (a = a_0 \text{ and } f_0 = f_{ad}) \), is illustrated in figure 6-18.

For small changes in stiffness \( (E_{cd}G_{cd} \approx E_cG_c) \), the influence of the multiplier is small. This is particularly true for low stiffness values. This disadvantage, when neglecting the first multiplier, however, is that changes in cross panel tensile strength are not accounted for. Particularly for the determination of wrinkling strength at elevated temperatures, it is a possible scenario that, for example, a newly developed mineral wool panel employs a glue layer which is not suitable for high temperatures. This may have little effect on the stiffness in the cross panel tensile test, but significantly influences the wrinkling strength. The use of equation 6.3-12 allows the determination of the influence of cross panel tensile strength not only in durability evaluation, but in a variety of other fields. For further investigations, it would be of particular interest to investigate if equation 6.3-12 is also valid for rapidly decreasing cross panel tensile strengths. This could be done in combination with the developed small scale wrinkling test. Samples with insufficient bonding

**Fig. 6-18 influence of first multiplier in equation 6.3-12 for different stiffness values and change thereof**
between face and core can be produced and tested relatively easily since the required size of
the samples is limited. The influence of the bad bonding on all properties can then be
evaluated through the small scale tests detailed in chapter 4.2, which would then also include
the wrinkling strength. A direct comparison with the proposed theoretical model then
becomes possible and is discussed in the proposal for further work.
7 Conclusions

This research has tried to improve the durability evaluation of sandwich panels. It was the aim to develop the currently, quality driven approach of durability evaluation towards a more quantity driven approach. This was particularly necessary as the current code allows a drop of 60% in performance of one single parameter (cross panel tensile strength) without any consequences for the important design parameters. The improvement was achieved on the basis of a variety of test results. This included not only the standard durability test procedures in climate cabinets, but also an outdoor testing facility, tests on old panels as well as a newly developed test procedure which allows the determination of the wrinkling strength on a small scale sample. The chemical backgrounds of ageing were investigated and it has been shown, that it is important to distinguish between diffusion free and diffusion tight core materials. These two material groups require different ageing scenarios. For each material group a model determining the relationship between artificial and natural ageing was developed. In a further step it was shown how deterioration in different mechanical parameters influence the overall strength of a sandwich panel. In particular, a relationship between cross panel tensile strength and wrinkling strength was developed. The model shows that it is a poor approach to judge the durability performance of a sandwich structure solely by its time dependent deterioration in cross panel tensile strength. Such an approach can even be dangerous, as, depending on the stiffness parameters of the core, a loss in cross panel strength can have little or severe impact on the wrinkling strength.

In detail the following conclusions can be drawn from the results of this study:

7.1 Small scale wrinkling test

A new, small scale test, determining the wrinkling strength of a sandwich panel, has been developed and tested. In order to overcome the problem of local damage in the area of load introduction, a bone shaped sample in combination with a glued T-shaped load application device was both glued and clamped to the specimen. The development of the test has shown that it is important to account for local deformations that occur in the full scale bending tests under the loaded areas. Only when this deformation is considered, comparable results are achieved with both, full scale and small scale wrinkling tests. Such additional deformation can be simulated with a combined load configuration, loading the samples in a bi-directional...
manner. For the investigation of the affect of durability on wrinkling strength, it is justifiable to omit the additional load device as it is sufficient to investigate the relative change in wrinkling strength.

This small scale wrinkling test is suitable for accelerated ageing in a climate cabinet which is not possible with a full sandwich panel because it is too big in size. As a result, the change in wrinkling strength over time was observed. The results obtained served to verify the theoretical model considering the influence of changes in cross panel tensile strength and stiffness on the wrinkling strength of a sandwich panel.

The new test method is suitable for other fields of application, such as estimation of the wrinkling strength for new sandwich cross sections. This is particularly important to panel developers as often only limited amounts of sandwich material is available during the development phase. The dimensions of these panels are often not sufficient for a full scale test.

For future applications, it is important to gather more experience with the small scale wrinkling test. In particular for ongoing investigations into the sandwich durability problem, the proposed test can be a strong tool.

### 7.2 Deterioration of mechanical properties over time

A variety of approaches to investigate the deterioration of mechanical properties over time were taken in this research. A total of 780 tests were conducted after test specimens had been exposed to artificial climates. This included not only cross panel tensile tests, which, nevertheless, represent the largest amount of tests, but also shear tests, compression tests, and small scale wrinkling tests. In addition, samples from sandwich panels that were at the end of their lifetime were tested and classified by comparing the obtained results for core material properties to those expected from experience for the determined core density. In combination, it could be shown that different material properties show different ageing behaviour. The influence of ageing on compressive panel strength in rigid foam (PUR) panels is that, after an initial drop, the core gains performance. At the same time, the related stiffness stays unaffected. Little effect was found on the shear strength and modulus of PUR panels. For cross panel tensile properties, ageing leads to a deterioration of strength and an increase in brittleness, which can be noticed through an increase in the corresponding elastic modulus. A
good conformity was obtained between the results from artificial ageing and natural ageing ("old" panels).

The influences of a variety of climates on the cross panel tensile strength for the core materials that are found in the sandwich panel market at the moment were conducted. It was discovered that different temperature and humidity combinations influence the speed of the ageing process. It was demonstrated that different core materials require different accelerated ageing scenarios. In principle, two categories of core material were distinguished. Firstly there are core materials that are open to diffusion like mineral wool and secondly there are diffusion tight core materials, such as polyurethane. An accelerated ageing scenario for diffusion tight core materials is presented on the base assumption that the diffusion process of oxygen into the cellular matrix is the responsible factor for material deterioration. For the core materials open to diffusion, the ageing scenario is based on the combination of high humidity and high temperature. Models connecting real time ageing and accelerated ageing are presented covering both categories of core material.

7.3 Investigation into internal panel climate

For mineral wool cores, the deterioration of binder resins was found to be responsible for deterioration in mechanical properties. Typically, a mix of two different binders is used in the production of mineral wools. One of the two binders is sensitive to hydrolysis reaction. The speed of the deterioration was observed to be temperature and humidity dependent. The presence of a second, less sensitive binder secures a minimum level of inter fibre connectivity and, therefore, a minimum level of structural performance.

For the first time, the actual internal climate of a mineral wool panel over a one year period has been determined. In order to achieve this information, a sandwich panel in an outdoor testing rig has been equipped with the latest technology in moisture sensors. This allows continuous monitoring and recording of relevant parameters at 10 minute intervals. The results obtained have shown that the internal panel climate, although clearly dependent on the surrounding climate, differs considerably from the external climate. This is basically due to the increasing panel temperature caused by global radiation onto the outer face of the panel, as well as the decelerated flow of humidity streams caused by the partial protection from the outer atmosphere. The results obtained were inserted in an existing model, which is based on experimental results from cross panel tensile tests on specimens subject to exposure under a
variety of temperature and humidity combinations. The model describes how the rate of
deterioration under different temperature and humidity combinations compare. The result is a
predication determining how long a sample must be aged under a certain climate to simulate a
chosen life cycle. The model was applied to a series of test results from cross panel tensile
tests after the exposure to a variety of climates and showed that, by manipulating the time axis
according to the model, all test series lead to the same result.

7.4 The determination of ageing in PUR panels based on oxygen
diffusion

Investigations into other fields of related research have shown that core materials that are
relatively tight in diffusion, such as polyurethane, require a diffusion related model,
establishing a connection between artificial and natural aging. Oxidation reactions in the
polymeric structure are held responsible for the deterioration of PUR structures. Oxygen,
however, is not present in fresh foam, where the cellular matrix is filled with a mixture of
carbon dioxide and a blowing agent. Over time, oxygen from the surrounding atmosphere
penetrates the cells and causes the chemical reaction to start. The progress of oxidation
reactions is indicated by a change in colour of the foam. For PUR samples, the foam colour
changes from cream white to brownish. The speed of diffusion is dependent on the exposed
surface to volume ratio of the investigated specimen, as well as the surrounding temperature.
A mathematic model that allows the comparison of diffusion speeds in small scale test
specimens under elevated temperatures with full scale panels under ambient temperatures was
presented. The model allows the determination of how long a sample with a particular
geometry needs to be exposed to a certain temperature to reach the same oxygen content and,
therefore, the same degree of ageing. For ease in modelling, conversion tables were produced,
allowing for direct comparison between the two most typical scenarios:

- 100 x 100 x thickness cuboid with faces in place exposed to a temperature of 90°C,
  which corresponds to the DUR 1 test in prEN 14 509, is compared to a full scale panel
  of 500 mm width at ambient temperatures
- 100 x 100 x thickness cuboid with faces in place exposed to a temperature of 90°C as
  in the previously described case, but this time compared to the more common full
  panel of 1000 mm width at ambient temperatures.
The proposed procedure for the first time actually allows finding a connection between accelerated and real time ageing, but in some areas it is based on uncertain assumptions. The results obtained on tensile strength values after artificial ageing do not show clear tendencies and indicate that the breakdown of the polymeric structure depends on more than one single factor. Future research from chemical experts must ascertain or enlarge the taken assumptions. During this research, it was noted that the chemical knowledge about deterioration of polyurethane is surprisingly small. This is particularly astonishing as PUR foam products have found their way into many every day items. It is, however, a special quality of sandwich constructions to exploit the mechanical properties of PUR foams in a structurally sensitive area, such as building construction.

7.5 Design consequences

This research has clearly shown that it is not sufficient to base the evaluation of sandwich durability solely on the deterioration of the cross panel tensile strength. It is particularly dangerous to allow a loss in strength without applying a correction factor for wrinkling strength. Apart from the cross panel tensile strength, it is very likely that other parameters are also influenced by durability-related deterioration. It is, therefore, necessary to relate durability not only on cross panel tension, but also to compression and shear. It is also important to consider not only the changes in mechanical strength, but also the changes in stiffness parameters. Stiffness parameters relate to the bedding strength activated and thus influence the effect a loss in cross panel strength has on the wrinkling strength of a sandwich structure. Furthermore, the ageing related change in stiffness parameters influence the wrinkling strength of a panel in general. The influence of ageing can only be predicted by considering all relevant core parameters.

A mathematical model describing, in particular, the influence of the loss in cross panel tensile strength and core stiffness on the wrinkling strength of a sandwich panel allows the prediction of the long term wrinkling strength of the panel. The model is based on assumptions on the pre-wrinkling behaviour of a continuously bedded sandwich face. Research into this deformation behaviour employing latest surveying technologies was used to verify the assumptions made on the form and shape of the pre-wrinkling deformation. The derived correcting factor
includes all important durability related changes. The proposed formula is easy to use, but complex in combining initial strength and stiffness values with the deterioration thereof. It was pointed out that a loss of 60% in cross panel tensile strength, which is seen as acceptable in prEN 14509, may indeed have little influence on the wrinkling strength of a sandwich panel. This is, however, not necessarily the case. There are possible panel configurations were a substantial loss in cross panel strength corresponds to a substantial loss in wrinkling strength. The significant factors are not only the change in strength and stiffness of a panel, but also the initial performance in strength and stiffness of that particular panel. These need to be determined through testing. It is therefore proposed to enlarge the current durability evaluation by implementing shear test and compression tests after ageing. These will then help to determine the durability implementing design values that can either be used directly in the design process or can be implemented in the proposed formula for the wrinkling strength. The obtained durability implementing deterioration factors shall either be stated on the CE label or included in the accompanying documents. While this requires an enlarged testing programme for the CE marking of sandwich panels, the results obtained in this research indicate that durability testing times for panels with diffusion tight core materials can be reduced significantly (80 days at 90°C instead of the currently required 168 days). For panels with diffusion free core materials, such as mineral wools, the results presented in this research indicate, that the ageing time proposed in the current version of prEN 14509 is not sufficient. This can be overcome either through prolonged testing time (at least 174 days at 70°C and 100% RH) or through higher test temperatures (e.g. 67 days at 90°C and 100% RH). The proposed procedure then accounts for all possible influences that deterioration may have on panel performance.

It is possible to increase the accuracy of other methods, determining the influence of changing stiffness parameters as is used, for example, in determination of the wrinkling strength at elevated temperatures or for normalisation calculations carried out, for example, to minimize the amount of necessary approval testing after substitution of foaming systems.
7.6 Future research

In some respects, this research raises more questions than it gives answers. The following areas have been identified as particularly important for future research. This does not only include research in the field of civil engineering but also includes investigations that can only be undertaken by or in conjunction with chemical experts.

1. When modelling the connection between accelerated ageing and natural ageing in polymeric structures, it was assumed that the presence of oxygen is the only factor determining the speed of deterioration. Although it is certain that oxygen-related breakage of polymeric links is one responsible factor for the deterioration of mechanical properties, the chemical background of these reactions is little investigated. Nothing is known about possible re-formation of polymers from decomposition products. Chemical experts should investigate and determine the polymeric structure of aged PUR foams. They should furthermore determine the composition of cellular gases over time and in different positions inside the foam structure. As a result the dependency of the chemical deterioration of the polymeric structure on the base of the oxygen content will be available.

2. The internal climate in a mineral wool sandwich panel was determined over a period of one single year in one single place. It is important to gather more information on such internal climates and, in particular, in real building applications. This can be done relatively easy by applying the same test devices as used in this research to different buildings. It will, however, be difficult to find a standard climate that can be used for the determination of an all-embracing accelerated ageing climate. By gathering a reasonable amount of test results it will however be possible to determine a worst case scenario. Together with local weather recordings it will be possible to find a dependency between the micro climate inside a sandwich structure and the surrounding atmosphere.

3. The modelling of necessary testing times for mineral wool core panels relies on a model implementing test results from aged samples tested in cross panel tensile strength. Currently there is only one single test series that has been performed on one single batch of panels available for implementation into the model. The assumptions coming with such procedure need to be based on more results. Further ageing tests on small samples under different climates that can then be evaluated in the model should be undertaken and the model should then be generalized.
4. The proposed model considering the influences of deterioration in strength and stiffness parameters in a sandwich core shows good compliance with the results obtained in the small scale wrinkling test. The investigated samples in this research showed, however, limited changes in parameters. Future research should prove that the model also works sufficiently accurately if the change in parameters is dramatic. For such research, again the small scale wrinkling test should be adopted. It is, for example, possible to weaken the glue layer in a mineral wool sample and study the influence with the help of this test.

5. Future research will establish the connection between change in cross panel tensile strength and stiffness and other properties. For this it is necessary to perform extensive test series, as have been undertaken on cross panel tests, also on other core parameters. In particular the ageing influences on the shear strength and stiffness as well as on cross panel compressive strength and stiffness are to be investigated. By establishing a connection between these parameters, an easier to perform durability tests, as the here proposed large variety of necessary tests would be obsolete, can be developed. Such conclusion can, however, only be reliably drawn from an adequate number of tests.
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prEN 14 509 *Self-supporting double skin metal faced insulating sandwich panels – Factory made products – Specification*


9 Appendix 1 results from artificial ageing
Overview of test results from artificial ageing

<table>
<thead>
<tr>
<th>Determination of standard deviation</th>
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</thead>
<tbody>
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<td>Polyurethane n-pentane blown (A) (90/15)</td>
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</tr>
<tr>
<td>Polyurethane HCFC blown (90/15)</td>
<td>4</td>
</tr>
<tr>
<td>Polyisocyanurate (90/15)</td>
<td>5</td>
</tr>
<tr>
<td>Expanded Polystyrene (A) (90/15)</td>
<td>6</td>
</tr>
<tr>
<td>Stone Wool, lamella (A) (90/15)</td>
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</tr>
<tr>
<td>Stone Wool, slabstock (90/15)</td>
<td>8</td>
</tr>
<tr>
<td>Phenolic Foam (90/15)</td>
<td>9</td>
</tr>
<tr>
<td>Glass Wool (90/15)</td>
<td>10</td>
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<tr>
<td>Expanded Polystyrene (50/80)</td>
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<tr>
<td>Expanded Polystyrene (90/60)</td>
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<tr>
<td>Expanded Polystyrene (65/100)</td>
<td>18</td>
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<tr>
<td>Expanded Polystyrene (50/90)</td>
<td>19</td>
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<tr>
<td>Polyurethane n-pentane blown (90/15)</td>
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</tr>
<tr>
<td>Polyurethane n-pentane blown (50/80)</td>
<td>21</td>
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<tr>
<td>Polyurethane n-pentane blown (90/60)</td>
<td>22</td>
</tr>
<tr>
<td>Polyurethane n-pentane blown (65/100)</td>
<td>23</td>
</tr>
<tr>
<td>Polyurethane n-pentane blown (50/90)</td>
<td>24</td>
</tr>
<tr>
<td>Polyurethane CO2 blown (90/15)</td>
<td>25</td>
</tr>
<tr>
<td>Polyurethane CO2 blown (50/80)</td>
<td>26</td>
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<tr>
<td>Polyurethane CO2 blown (90/60)</td>
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<td>Polyurethane CO2 blown (65/100)</td>
<td>28</td>
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<tr>
<td>Polyurethane CO2 blown (50/90)</td>
<td>29</td>
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<tr>
<td>Stone Wool, lamella (90/15)</td>
<td>30</td>
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<tr>
<td>Stone Wool, lamella (50/80)</td>
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<tr>
<td>Stone Wool, lamella (90/60)</td>
<td>32</td>
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<tr>
<td>Stone Wool, lamella (65/100)</td>
<td>33</td>
</tr>
<tr>
<td>Stone Wool, lamella (50/90)</td>
<td>34</td>
</tr>
</tbody>
</table>

Key:

Type of material: (test temperature[°C] / test humidity[% RH])
**Determination of standard deviation**

For a set of comparable test results, the uniformity of the obtained results can be evaluated by looking at the following important parameters:

- number of tests \([N]\)
- average of test results \([\bar{x}]\)
- standard deviation \([\sigma_x]\)

Here, the standard deviation or root mean square (rms) is a measured value of the statistical spread. It is the square root of the variance, thus having the same dimension as the individual members of the set.

\[
\sigma_x = \sqrt{\frac{1}{N} \sum_{i=1}^{N} (x_i - \bar{x})^2}
\]

where

- \(\sigma_x\): standard deviation
- \(\bar{x}\): average of test results
- \(N\): number of tests
- \(x_i\): test result of element \(i\)

The average of test results is given by

\[
\bar{x} = \frac{1}{N} \sum_{i=1}^{N} x_i
\]
Polyurethane n-pentane blown (A) (90/15)

Ageing condition: 90°C RH < 15%

Test: tension perpendicular to face

SID: 2.6

Tension Capacity [N/mm²]

<table>
<thead>
<tr>
<th>days</th>
<th>σ₁</th>
<th>σ₂</th>
<th>σ₃</th>
<th>σ₄</th>
<th>σ₅</th>
<th>avrg σ</th>
<th>rms³</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
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<td>0.111</td>
<td>0.112</td>
<td>0.113</td>
<td>0.096</td>
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<tr>
<td>7</td>
<td>0.112</td>
<td>0.121</td>
<td>0.147</td>
<td>0.134</td>
<td>0.098</td>
<td>0.126</td>
<td>0.014</td>
</tr>
<tr>
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<td>0.093</td>
<td>0.091</td>
<td>0.094</td>
<td>0.005</td>
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<td>0.098</td>
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<td>0.116</td>
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<td>0.111</td>
<td>0.009</td>
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<tr>
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<td>0.111</td>
<td>0.110</td>
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<td>0.111</td>
<td>0.112</td>
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Elastic Modulus [N/mm²]

<table>
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<tr>
<th>days</th>
<th>E₁</th>
<th>E₂</th>
<th>E₃</th>
<th>E₄</th>
<th>E₅</th>
<th>avrg E</th>
<th>rms³</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
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<td>4.156</td>
<td>4.199</td>
<td>4.609</td>
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<td>0.021</td>
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<td>5.252</td>
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<td>3.740</td>
<td>4.516</td>
<td>0.628</td>
</tr>
<tr>
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<td>3.76</td>
<td>3.43</td>
<td>4.58</td>
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</tr>
</tbody>
</table>

7 days 28 days 56 days 90 days

1 RH - relative humidity
2 SID - specimen identification number (allows to identify source and producer)
3 rms - root mean square error

Appendix 1 page -3-
Polyurethane HCFC blown (90/15)

Aging condition: 90°C RH < 15%
SID: 5.6

Test: tension perpendicular to face

<table>
<thead>
<tr>
<th>Tension Capacity [N/mm²]</th>
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<th>$\sigma_{\text{test 2}}$</th>
<th>$\sigma_{\text{test 3}}$</th>
<th>$\sigma_{\text{test 4}}$</th>
<th>$\sigma_{\text{test 5}}$</th>
<th>avrg $\sigma$</th>
<th>rms</th>
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<td>0.008</td>
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<td>0.08</td>
<td>0.075</td>
<td>0.086</td>
<td>0.016</td>
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<td>0.121</td>
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<td>0.11</td>
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<td>0.128</td>
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<td></td>
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<td>0.007</td>
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<table>
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<th>$E_{\text{test 2}}$</th>
<th>$E_{\text{test 3}}$</th>
<th>$E_{\text{test 4}}$</th>
<th>$E_{\text{test 5}}$</th>
<th>avrg E</th>
<th>rms</th>
</tr>
</thead>
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</tbody>
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Appendix 1 page -4-
**Polyisocyanurate (90/15)**

**Ageing condition:** 90°C RH < 15%

**Test:** tension perpendicular to face

<table>
<thead>
<tr>
<th>Time (days)</th>
<th>Test 1</th>
<th>Test 2</th>
<th>Test 3</th>
<th>Test 4</th>
<th>Test 5</th>
<th>Avg σ</th>
<th>RMS</th>
</tr>
</thead>
<tbody>
<tr>
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<td>0.134</td>
<td>0.114</td>
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<td>0.096</td>
<td>0.095</td>
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</tr>
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<td>0.008</td>
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**Elastic Modulus [N/mm²]**

<table>
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<tr>
<th>Time (days)</th>
<th>Test 1</th>
<th>Test 2</th>
<th>Test 3</th>
<th>Test 4</th>
<th>Test 5</th>
<th>Avg E</th>
<th>RMS</th>
</tr>
</thead>
<tbody>
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<td>0.113</td>
<td>0.149</td>
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<td>7.042</td>
<td>7.042</td>
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</tr>
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<td>8.669</td>
<td>8.084</td>
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Appendix 1 page -5-
Expanded Polystyrene (A) (90/15)

Ageing condition: 90°C RH < 15%

SID: 1.7

Test: tension perpendicular to face

<table>
<thead>
<tr>
<th>Days</th>
<th>Test 1</th>
<th>Test 2</th>
<th>Test 3</th>
<th>Test 4</th>
<th>Test 5</th>
<th>Average</th>
<th>RMS</th>
</tr>
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</tr>
<tr>
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<td>0.112</td>
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<td>0.066</td>
<td>0.076</td>
<td>0.086</td>
<td>0.008</td>
</tr>
<tr>
<td>28</td>
<td>0.066</td>
<td>0.056</td>
<td>0.061</td>
<td>0.062</td>
<td>0.045</td>
<td>0.053</td>
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<td>0.084</td>
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<td>0.065</td>
<td>0.098</td>
<td>0.106</td>
<td>0.098</td>
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<table>
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<tr>
<th>Days</th>
<th>Test 1</th>
<th>Test 2</th>
<th>Test 3</th>
<th>Test 4</th>
<th>Test 5</th>
<th>Average</th>
<th>RMS</th>
</tr>
</thead>
<tbody>
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<td>9.976</td>
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</table>

7 days  28 days  56 days  90 days

Appendix 1 page -6-
Stone Wool, lamella (A) (90/15)

Ageing condition: 90°C RH < 15%
SID: 4.3

Test: tension perpendicular to face

Tension Capacity [N/mm²]

<table>
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<tr>
<th>days</th>
<th>(\sigma_{\text{test} 1})</th>
<th>(\sigma_{\text{test} 2})</th>
<th>(\sigma_{\text{test} 3})</th>
<th>(\sigma_{\text{test} 4})</th>
<th>(\sigma_{\text{test} 5})</th>
<th>avrg (\sigma)</th>
<th>rms</th>
</tr>
</thead>
<tbody>
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<td>0.076</td>
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<td>0.079</td>
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<td>0.006</td>
</tr>
<tr>
<td>7</td>
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<td>0.071</td>
<td>0.091</td>
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<td>0.007</td>
</tr>
<tr>
<td>28</td>
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<td>0.071</td>
<td>0.063</td>
<td>0.063</td>
<td>0.079</td>
<td>0.082</td>
<td>0.002</td>
</tr>
<tr>
<td>56</td>
<td>0.083</td>
<td>0.068</td>
<td>0.069</td>
<td>0.075</td>
<td>0.082</td>
<td>0.071</td>
<td>0.003</td>
</tr>
<tr>
<td>90</td>
<td>0.082</td>
<td>0.074</td>
<td>0.078</td>
<td>0.082</td>
<td>0.082</td>
<td>0.081</td>
<td>0.002</td>
</tr>
<tr>
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<td>0.076</td>
<td>0.071</td>
<td>0.071</td>
<td>0.082</td>
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</tbody>
</table>

Elastic Modulus [N/mm²]

<table>
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<tr>
<th>days</th>
<th>(E_{\text{test} 1})</th>
<th>(E_{\text{test} 2})</th>
<th>(E_{\text{test} 3})</th>
<th>(E_{\text{test} 4})</th>
<th>(E_{\text{test} 5})</th>
<th>avrg E</th>
<th>rms</th>
</tr>
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<tbody>
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<tr>
<td>28</td>
<td>8,509</td>
<td>8,742</td>
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<td>10,076</td>
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<td>9,303</td>
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<td>9,166</td>
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</table>
Stone Wool, slabstock (90/15)

Ageing condition: 90°C RH < 15%
SID: 4.5

Test: tension perpendicular to face

### Tension Capacity [N/mm²]

<table>
<thead>
<tr>
<th>days</th>
<th>$\sigma_{\text{test 1}}$</th>
<th>$\sigma_{\text{test 2}}$</th>
<th>$\sigma_{\text{test 3}}$</th>
<th>$\sigma_{\text{test 4}}$</th>
<th>$\sigma_{\text{test 5}}$</th>
<th>$\sigma_{\text{avrg}}$</th>
<th>$\sigma_{\text{rms}}$</th>
</tr>
</thead>
<tbody>
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<td>0</td>
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<td>0.035</td>
<td>0.030</td>
<td>0.042</td>
<td>0.040</td>
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### Elastic Modulus [N/mm²]

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<th>$E_{\text{avrg}}$</th>
<th>$E_{\text{rms}}$</th>
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*average of 9 tests*
Phenolic Foam (90/15)

Ageing condition: 90°C RH < 15%
SID: 7.7

Test: tension perpendicular to face

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<th>σ₂</th>
<th>σ₃</th>
<th>σ₄</th>
<th>σ₅</th>
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<th>rms</th>
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<td>0.001</td>
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<td>0.024</td>
<td>0.005</td>
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<tr>
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<td>0.016</td>
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<td>0.012</td>
<td>0.033</td>
<td>0.024</td>
<td>0.005</td>
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<th>E₂</th>
<th>E₃</th>
<th>E₄</th>
<th>E₅</th>
<th>avrg E</th>
<th>rms</th>
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<td>2.713</td>
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<td>0.863</td>
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</table>

7 days 28 days 56 days 90 days

Appendix 1 page -9-
Glas Wool (90/15)

Ageing condition: 90°C  RH < 15%
SID: 8.9
Test: tension perpendicular to face

**Tension Capacity [N/mm²]**

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<th>days</th>
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<th>$\sigma_{\text{test 3}}$</th>
<th>$\sigma_{\text{test 4}}$</th>
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<th>rms</th>
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<tbody>
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<td>0.253</td>
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<td>0.159</td>
<td>0.160</td>
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<tr>
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<td>0.221</td>
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<td>0.243</td>
<td>0.185</td>
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<tr>
<td>56</td>
<td>0.215</td>
<td>0.178</td>
<td>0.175</td>
<td>0.216</td>
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<td>0.196</td>
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<tr>
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**Elastic Modulus [N/mm²]**

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<th>$E_{\text{test 3}}$</th>
<th>$E_{\text{test 4}}$</th>
<th>$E_{\text{test 5}}$</th>
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<th>rms</th>
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<td>23,522</td>
<td>21,597</td>
<td>15,822</td>
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Appendix 1 page -10-
Polyurethane n-pentane blown (90/15)

Ageing condition: 90°C RH < 15%
SID: 2355

Test: tension perpendicular to face

---

Tension Capacity [N/mm²]

<table>
<thead>
<tr>
<th>days</th>
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<th>$\sigma_{test 2}$</th>
<th>$\sigma_{test 3}$</th>
<th>$\sigma_{test 4}$</th>
<th>$\sigma_{test 5}$</th>
<th>avg $\sigma$</th>
<th>rms</th>
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<td>0,112</td>
<td>0,107</td>
<td>0,106</td>
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<td>0,102</td>
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Elastic Modulus [N/mm²]

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<th>$E_{test 4}$</th>
<th>$E_{test 5}$</th>
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<th>rms</th>
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Appendix 1 page -11-
Polyurethane n-pentane blown (90/15)

Aging condition: 90°C RH < 15%

SID: 2355

Test: compression perpendicular to face

Compression Capacity [N/mm²]

<table>
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<th>σ_test 3</th>
<th>σ_test 4</th>
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<th>rms</th>
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<td>0.094</td>
<td>0.094</td>
<td>0.094</td>
<td>0.094</td>
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Elastic Modulus [N/mm²]

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Polyurethane n-pentane blown (19/15)

Ageing condition: 90°C RH < 15%
SID: 2355

Test: shear on short beam

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<th>σ_{test 4}</th>
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<th>rms</th>
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<td>0.155</td>
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<td>0.153</td>
<td>0.178</td>
<td>0.146</td>
<td>0.179</td>
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<th>E_{test 2}</th>
<th>E_{test 3}</th>
<th>E_{test 4}</th>
<th>E_{test 5}</th>
<th>avg E</th>
<th>rms</th>
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Appendix 1 page -13-
Polyurethane n-pentane blown (90/15)

Aging condition: 90°C RH < 15%
Test: small scale wrinkle

Wrinkling Capacity [N/mm²]

<table>
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<th>days</th>
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<th>Test 3</th>
<th>Test 4</th>
<th>Test 5</th>
<th>avg σ</th>
<th>rms</th>
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*average of four tests due to lack of test five*
Expanded Polystyrene (90/15)

Aging condition: 90°C RH < 15%
SID: 1.1
Test: tension perpendicular to face

Tension Capacity [N/mm²]

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<th>Etest 3</th>
<th>Etest 4</th>
<th>Etest 5</th>
<th>avrg E</th>
<th>rms</th>
</tr>
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<td>0.133</td>
<td>0.082</td>
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<tr>
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<td>0.089</td>
<td>0.074</td>
<td>0.081</td>
<td>0.070</td>
<td>0.084</td>
<td>0.003</td>
</tr>
<tr>
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<td>0.069</td>
<td>0.071</td>
<td>0.065</td>
<td>0.068</td>
<td>0.068</td>
<td>0.068</td>
<td>0.002</td>
</tr>
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<td>0.067</td>
<td>0.056</td>
<td>0.065</td>
<td>0.085</td>
<td>0.063</td>
<td>0.008</td>
</tr>
<tr>
<td>90</td>
<td>0.078</td>
<td>0.056</td>
<td>0.056</td>
<td>0.059</td>
<td>0.079</td>
<td>0.079</td>
<td>0.014</td>
</tr>
</tbody>
</table>

Elastic Modulus [N/mm²]

<table>
<thead>
<tr>
<th>days</th>
<th>Etest 1</th>
<th>Etest 2</th>
<th>Etest 3</th>
<th>Etest 4</th>
<th>Etest 5</th>
<th>avrg E</th>
<th>rms</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>5.394</td>
<td>4.656</td>
<td>4.468</td>
<td>4.413</td>
<td>4.737</td>
<td>4.737</td>
<td>0.389</td>
</tr>
<tr>
<td>7</td>
<td>5.820</td>
<td>5.888</td>
<td>5.948</td>
<td>5.760</td>
<td>5.866</td>
<td>5.866</td>
<td>0.084</td>
</tr>
<tr>
<td>28</td>
<td>5.903</td>
<td>6.050</td>
<td>5.490</td>
<td>4.051</td>
<td>4.879</td>
<td>4.879</td>
<td>0.067</td>
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<td>5.860</td>
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<td>5.364</td>
<td>0.710</td>
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<td>4.821</td>
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<td>5.066</td>
<td>5.009</td>
<td>5.009</td>
<td>0.235</td>
</tr>
</tbody>
</table>

5 average of four tests due to lack of test five
6 average of four tests due to lack of test five
Expanded Polystyrene (50/80)

Aging condition: 50°C 80% RH
SID: 1.1
Test: tension perpendicular to face

Tension Capacity [N/mm²]

<table>
<thead>
<tr>
<th>days</th>
<th>$\sigma_{\text{test 1}}$</th>
<th>$\sigma_{\text{test 2}}$</th>
<th>$\sigma_{\text{test 3}}$</th>
<th>$\sigma_{\text{test 4}}$</th>
<th>$\sigma_{\text{test 5}}$</th>
<th>avg $\sigma$</th>
<th>rms</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.147</td>
<td>0.121</td>
<td>0.132</td>
<td>0.133</td>
<td>0.133</td>
<td>0.133⁷</td>
<td>0.009</td>
</tr>
<tr>
<td>7</td>
<td>0.131</td>
<td>0.101</td>
<td>0.154</td>
<td></td>
<td></td>
<td>0.129</td>
<td>0.022</td>
</tr>
<tr>
<td>56</td>
<td>0.146</td>
<td>0.134</td>
<td>0.133</td>
<td></td>
<td></td>
<td>0.138</td>
<td>0.006</td>
</tr>
<tr>
<td>90</td>
<td>0.112</td>
<td>0.109</td>
<td>0.104</td>
<td></td>
<td></td>
<td>0.108</td>
<td>0.003</td>
</tr>
</tbody>
</table>

Elastic Modulus [N/mm²]

<table>
<thead>
<tr>
<th>days</th>
<th>$E_{\text{test 1}}$</th>
<th>$E_{\text{test 2}}$</th>
<th>$E_{\text{test 3}}$</th>
<th>$E_{\text{test 4}}$</th>
<th>$E_{\text{test 5}}$</th>
<th>avg $E$</th>
<th>rms</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>5,394</td>
<td>4,656</td>
<td>4,485</td>
<td>4,413</td>
<td>4,815</td>
<td>4,737</td>
<td>0.389</td>
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<td>5,016</td>
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<td>0.485</td>
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</tbody>
</table>

7 average of four tests due to lack of test five

Appendix 1 page -16-
Expanded Polystyrene (90/60)

Ageing condition: 90°C 60% RH

SID: 1.1

Test: tension perpendicular to face

<table>
<thead>
<tr>
<th>Tension Capacity [N/mm²]</th>
<th>days</th>
<th>E_{test 1}</th>
<th>E_{test 2}</th>
<th>E_{test 3}</th>
<th>E_{test 4}</th>
<th>E_{test 5}</th>
<th>avg E</th>
<th>rms</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0</td>
<td>5,394</td>
<td>4,656</td>
<td>4,485</td>
<td>4,413</td>
<td>4,737</td>
<td>4,737</td>
<td>0,389</td>
</tr>
<tr>
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<td>4,553</td>
<td></td>
<td>4,809</td>
<td>4,809</td>
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<tr>
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<td>28</td>
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<td>3,877</td>
<td>4,243</td>
<td></td>
<td>3,826</td>
<td>3,826</td>
<td>0,363</td>
</tr>
<tr>
<td>Total loss of face-core adhesion during exposure period</td>
<td>56</td>
<td>0,000</td>
<td>0,000</td>
<td>0,000</td>
<td></td>
<td>0,000</td>
<td>0,000</td>
<td></td>
</tr>
<tr>
<td>Total loss of face-core adhesion during exposure period</td>
<td>90</td>
<td>0,000</td>
<td>0,000</td>
<td>0,000</td>
<td></td>
<td>0,000</td>
<td>0,000</td>
<td></td>
</tr>
</tbody>
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<table>
<thead>
<tr>
<th>Elastic Modulus [N/mm²]</th>
<th>days</th>
<th>E_{test 1}</th>
<th>E_{test 2}</th>
<th>E_{test 3}</th>
<th>E_{test 4}</th>
<th>E_{test 5}</th>
<th>avg E</th>
<th>rms</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0</td>
<td>0,147</td>
<td>0,121</td>
<td>0,132</td>
<td>0,133</td>
<td>0,133</td>
<td>0,133</td>
<td>0,008</td>
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<tr>
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<td>0,093</td>
<td>0,127</td>
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<td>0,095</td>
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<tr>
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<td>0,111</td>
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<td>0,110</td>
<td>0,110</td>
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<tr>
<td>Total loss of face-core adhesion during exposure period</td>
<td>56</td>
<td>0,000</td>
<td>0,000</td>
<td>0,000</td>
<td></td>
<td>0,000</td>
<td>0,000</td>
<td></td>
</tr>
<tr>
<td>Total loss of face-core adhesion during exposure period</td>
<td>90</td>
<td>0,000</td>
<td>0,000</td>
<td>0,000</td>
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<td>0,000</td>
<td>0,000</td>
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</tr>
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</table>

⁻ average of four tests due to lack of test five

7 days 28 days 56 days 90 days
Expanded Polystyrene (65/100)

Ageing condition: 65°C 100% RH  
SID: 1.1

Test: tension perpendicular to face

<table>
<thead>
<tr>
<th>Tension Capacity [N/mm²]</th>
<th>days</th>
<th>0</th>
<th>7</th>
<th>28</th>
<th>56</th>
<th>90</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
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<td>0.146</td>
<td>0.143</td>
<td>0.146</td>
</tr>
<tr>
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</tr>
<tr>
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<td>0.086</td>
<td>0.090</td>
<td>0.127</td>
<td>0.148</td>
<td>0.145</td>
</tr>
<tr>
<td></td>
<td>56</td>
<td>0.126</td>
<td>0.146</td>
<td>0.154</td>
<td>0.146</td>
<td>0.145</td>
</tr>
<tr>
<td></td>
<td>90</td>
<td>0.092</td>
<td>0.132</td>
<td>0.090</td>
<td>0.132</td>
<td>0.118</td>
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</table>

<table>
<thead>
<tr>
<th>Elastic Modulus [N/mm²]</th>
<th>days</th>
<th>0</th>
<th>7</th>
<th>28</th>
<th>56</th>
<th>90</th>
</tr>
</thead>
<tbody>
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<td>-</td>
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<tr>
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<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
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<td>-</td>
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<td>90</td>
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<td>-</td>
<td>-</td>
<td>-</td>
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</tr>
</tbody>
</table>

7 days  28 days  56 days  90 days

Appendix 1 page -18-
Expanded Polystyrene (50/90)

Ageing condition: 50°C 90% RH
SID: 1.1

Test: tension perpendicular to face

Tension Capacity [N/mm²]

<table>
<thead>
<tr>
<th>days</th>
<th>σ_{test 1}</th>
<th>σ_{test 2}</th>
<th>σ_{test 3}</th>
<th>σ_{test 4}</th>
<th>σ_{test 5}</th>
<th>avrg σ</th>
<th>rms</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.144</td>
<td>0.147</td>
<td>0.146</td>
<td>0.143</td>
<td>0.142</td>
<td>0.146</td>
<td>0.002</td>
</tr>
<tr>
<td>7</td>
<td>0.120</td>
<td>0.154</td>
<td>0.164</td>
<td>0.120</td>
<td>0.121</td>
<td>0.121</td>
<td>0.001</td>
</tr>
<tr>
<td>28</td>
<td>0.128</td>
<td>0.121</td>
<td>0.106</td>
<td>0.143</td>
<td>0.132</td>
<td>0.127</td>
<td>0.006</td>
</tr>
<tr>
<td>56</td>
<td>0.113</td>
<td>0.156</td>
<td>0.118</td>
<td>0.111</td>
<td>0.153</td>
<td>0.114</td>
<td>0.003</td>
</tr>
<tr>
<td>90</td>
<td>0.156</td>
<td>0.150</td>
<td>0.155</td>
<td>0.148</td>
<td>0.153</td>
<td>0.151</td>
<td>0.002</td>
</tr>
</tbody>
</table>

Elastic Modulus [N/mm²]

<table>
<thead>
<tr>
<th>days</th>
<th>E_{test 1}</th>
<th>E_{test 2}</th>
<th>E_{test 3}</th>
<th>E_{test 4}</th>
<th>E_{test 5}</th>
<th>avrg E</th>
<th>rms</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>7</td>
<td>28</td>
<td>56</td>
<td>90</td>
<td>7</td>
<td>28</td>
<td>56</td>
</tr>
</tbody>
</table>

Appendix 1 page -19-
Polyurethane n-pentane blown (90/15)

Ageing condition: 90°C RH < 15%
Test: tension perpendicular to face

Tension Capacity [N/mm²]

<table>
<thead>
<tr>
<th>days</th>
<th>( \sigma_{\text{Test 1}} )</th>
<th>( \sigma_{\text{Test 2}} )</th>
<th>( \sigma_{\text{Test 3}} )</th>
<th>( \sigma_{\text{Test 4}} )</th>
<th>( \sigma_{\text{Test 5}} )</th>
<th>( \text{avrg } \sigma )</th>
<th>rms</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.108</td>
<td>0.105</td>
<td>0.094</td>
<td>0.092</td>
<td>0.102</td>
<td>0.102</td>
<td>0.006</td>
</tr>
<tr>
<td>7</td>
<td>0.123</td>
<td>0.113</td>
<td>0.118</td>
<td>0.124</td>
<td>0.116</td>
<td>0.116</td>
<td>0.006</td>
</tr>
<tr>
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<td>0.110</td>
<td>0.027</td>
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<td>0.151</td>
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<td>0.131</td>
<td>0.131</td>
<td>0.013</td>
</tr>
<tr>
<td>90</td>
<td>0.097</td>
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<td>0.123</td>
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Elastic Modulus [N/mm²]

<table>
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<th>( E_{\text{Test 1}} )</th>
<th>( E_{\text{Test 2}} )</th>
<th>( E_{\text{Test 3}} )</th>
<th>( E_{\text{Test 4}} )</th>
<th>( E_{\text{Test 5}} )</th>
<th>( \text{avrg } E )</th>
<th>rms</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>4,910</td>
<td>4,028</td>
<td>4,600</td>
<td>4,668</td>
<td>4,633</td>
<td>4,633</td>
<td>0,368</td>
</tr>
<tr>
<td>7</td>
<td>4,091</td>
<td>5,332</td>
<td>5,001</td>
<td>4,665</td>
<td>5,014</td>
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<tr>
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<td>5,152</td>
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<td>6,329</td>
<td>5,218</td>
<td>6,166</td>
<td>6,166</td>
<td>0,562</td>
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<td>7,828</td>
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</table>

7 days 28 days 56 days 90 days

average of four tests due to lack of test five
Polyurethane n-pentane blown (50/80)

Aging condition: 50°C 80% RH
S1D: 2.2

Test: tension perpendicular to face

### Tension Capacity [N/mm²]

<table>
<thead>
<tr>
<th>days</th>
<th>σ̅ₜₐₜₜ ₁</th>
<th>σ̅ₜₐₜₜ ₂</th>
<th>σ̅ₜₐₜₜ ₃</th>
<th>σ̅ₜₐₜₜ ₄</th>
<th>σ̅ₜₐₜₜ ₅</th>
<th>avg σ</th>
<th>rms</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.106</td>
<td>0.105</td>
<td>0.094</td>
<td>0.123</td>
<td>0.092</td>
<td>0.102</td>
<td>0.006</td>
</tr>
<tr>
<td>7</td>
<td>0.102</td>
<td>0.113</td>
<td>0.115</td>
<td></td>
<td></td>
<td>0.110</td>
<td>0.006</td>
</tr>
<tr>
<td>28</td>
<td>0.109</td>
<td>0.097</td>
<td>0.086</td>
<td></td>
<td></td>
<td>0.098</td>
<td>0.008</td>
</tr>
<tr>
<td>56</td>
<td>0.098</td>
<td>0.108</td>
<td>0.095</td>
<td></td>
<td></td>
<td>0.101</td>
<td>0.008</td>
</tr>
<tr>
<td>90</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Elastic Modulus [N/mm²]

<table>
<thead>
<tr>
<th>days</th>
<th>Eₜₐₜₜ ₁</th>
<th>Eₜₐₜₜ ₂</th>
<th>Eₜₐₜₜ ₃</th>
<th>Eₜₐₜₜ ₄</th>
<th>Eₜₐₜₜ ₅</th>
<th>avg E</th>
<th>rms</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>4.910</td>
<td>4.028</td>
<td>4.600</td>
<td>4.980</td>
<td>4.911</td>
<td>4.523</td>
<td>0.366</td>
</tr>
<tr>
<td>7</td>
<td>5.203</td>
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<td>5.780</td>
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<td></td>
<td>5.870</td>
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<td>5.668</td>
<td>0.632</td>
</tr>
<tr>
<td>90</td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

7 days 28 days 56 days 90 days
Polyurethane n-pentane blown (90/60)

Aging condition: 90°C 60% RH
SID: 2.2

Test: tension perpendicular to face

<table>
<thead>
<tr>
<th>Tension Capacity [N/mm²]</th>
<th>days</th>
<th>Etest 1</th>
<th>Etest 2</th>
<th>Etest 3</th>
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7 days 28 days 56 days 90 days

Appendix 1 page -22-
Polyurethane n-pentane blown (65/100)

Ageing condition: 65°C 100% RH
SID: 2.2
Test: tension perpendicular to face (F)

<table>
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<th>Eₜₐˢᵗ ₂</th>
<th>Eₜₐˢᵗ ₃</th>
<th>Eₜₐˢᵗ ₄</th>
<th>Eₜₐˢᵗ ₅</th>
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<th>Eₜₐˢᵗ ₂</th>
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<th>Eₜₐˢᵗ ₄</th>
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7 days  28 days  56 days  90 days

Appendix 1 page -23-
Polyurethane n-pentane blown (50/90)

Ageing condition: 50°C 90% RH  
Test: tension perpendicular to face (F)  
SID: 2.2

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<th>σ₃₀₀₀</th>
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<td>0.037</td>
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<th>E₂₀₀₀</th>
<th>E₃₀₀₀</th>
<th>E₄₀₀₀</th>
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<th>rms</th>
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Appendix 1 page -24-
Polyurethane CO\textsubscript{2} blown (90/15)

Ageing condition: 90°C RH < 15%

Test: tension perpendicular to face

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<th>(\sigma_{test2})</th>
<th>(\sigma_{test3})</th>
<th>(\sigma_{test4})</th>
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<th>(E_{test5})</th>
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Appendix 1 page -25-
Polyurethane CO₂ blown (50/80)

Ageing condition: 50°C 80% RH
SID: 3.3

Test: tension perpendicular to face

Tension Capacity [N/mm²]

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<th>Test 3</th>
<th>Test 4</th>
<th>Test 5</th>
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<th>rms</th>
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Elastic Modulus [N/mm²]

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<th>Test 3</th>
<th>Test 4</th>
<th>Test 5</th>
<th>avg E</th>
<th>rms</th>
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7 days 28 days 56 days 90 days

Appendix 1 page -26-
Polyurethane CO\textsubscript{2} blown (90/60)

Aging condition: \hspace{1cm} 90°C \hspace{1cm} 60% RH

Test: tension perpendicular to face

| Tension Capacity [N/mm\textsuperscript{2}] | avg $\sigma$ | rms $\sigma$
|---|---|---|
| days | $\sigma_{\text{test 1}}$ | $\sigma_{\text{test 2}}$ | $\sigma_{\text{test 3}}$ | $\sigma_{\text{test 4}}$ | $\sigma_{\text{test 5}}$ | $\sigma_{\text{avg}}$ | $\sigma_{\text{rms}}$
| 0  | 0,160  | 0,123  | 0,136  | 0,132  | 0,144  | 0,130  | 0,065
| 7  | 0,112  | 0,128  | 0,163  | 0,118  | 0,121  | 0,134  | 0,021
| 28 | 0,116  | 0,105  | 0,134  | 0,064  | 0,030  | 0,118  | 0,012
| 56 | 0,102  | 0,060  | 0,029  | 0,060  | 0,018  | 0,102  | 0,018
| 90 | 0,035  | 0,076  | 0,069  | 0,060  | 0,018  | 0,035  | 0,018

| Elastic Modulus [N/mm\textsuperscript{2}] | avg $E$ | rms $E$
|---|---|---|
| days | $E_{\text{test 1}}$ | $E_{\text{test 2}}$ | $E_{\text{test 3}}$ | $E_{\text{test 4}}$ | $E_{\text{test 5}}$ | $E_{\text{avg}}$ | $E_{\text{rms}}$
| 0  | 6,451  | 6,661  | 5,841  | 5,797  | 5,681  | 6,130  | 0,366
| 7  | 5,574  | 6,718  | 7,278  | 6,455  | 6,944  | 6,623  | 0,347
| 28 | 7,224  | 7,152  | 6,455  | 5,750  | 5,750  | 6,456  | 1,816
| 56 | 8,151  | 5,333  | 3,765  | 6,456  | 6,456  | 5,333  | 0,850
| 90 | 5,287  | 6,802  | 7,280  | 5,287  | 5,287  | 6,802  | 0,850

Appendix 1 page -27-
Polyurethane CO\textsubscript{2} blown (65/100)

Ageing condition: 65\degree C  100\% RH  
Test: tension perpendicular to face (F)

Tension Capacity [N/mm\textsuperscript{2}]

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<th>(\sigma_{\text{Test 3}})</th>
<th>(\sigma_{\text{Test 4}})</th>
<th>(\sigma_{\text{Test 5}})</th>
<th>\text{avr g} (\sigma)</th>
<th>rms</th>
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Elastic Modulus [N/mm\textsuperscript{2}]

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<th>(E_{\text{Test 2}})</th>
<th>(E_{\text{Test 3}})</th>
<th>(E_{\text{Test 4}})</th>
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</tbody>
</table>

7 days 28 days 56 days 90 days

Appendix 1 page -28-
Polyurethane CO₂ blown (50/90)

Ageing condition: 50°C 90% RH

Test: tension perpendicular to face (F)

<table>
<thead>
<tr>
<th>Tension Capacity [N/mm²]</th>
<th>days</th>
<th>utens 1</th>
<th>utens 2</th>
<th>utens 3</th>
<th>utens 4</th>
<th>utens 5</th>
<th>avg u</th>
<th>rms</th>
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<td>0.072</td>
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<td>0.084</td>
<td>0.124</td>
<td>0.100</td>
<td>0.006</td>
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<td>0.111</td>
<td>0.111</td>
<td>0.084</td>
<td>0.124</td>
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<td>0.113</td>
<td>0.009</td>
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<th>days</th>
<th>Eutens 1</th>
<th>Eutens 2</th>
<th>Eutens 3</th>
<th>Eutens 4</th>
<th>Eutens 5</th>
<th>avg E</th>
<th>rms</th>
</tr>
</thead>
<tbody>
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<td></td>
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<td>0.124</td>
<td>0.147</td>
<td>0.143</td>
<td>0.062</td>
<td>0.061</td>
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<td>0.002</td>
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7 days  28 days  56 days  90 days
Stone Wool, lamella (90/15)

Ageing condition: 90°C RH < 15%
SID: 4.4

Test: tension perpendicular to face

Tension Capacity [N/mm²]

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<tr>
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<th>σ_{test 1}</th>
<th>σ_{test 2}</th>
<th>σ_{test 3}</th>
<th>σ_{test 4}</th>
<th>σ_{test 5}</th>
<th>avrg σ</th>
<th>rms</th>
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</thead>
<tbody>
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<td>0.177</td>
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<td>0.170</td>
<td>0.165</td>
<td>0.148</td>
<td>0.196</td>
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</tr>
<tr>
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<td>0.185</td>
<td>0.160</td>
<td>0.165</td>
<td>0.148</td>
<td>0.196</td>
<td>0.170</td>
<td>0.011</td>
</tr>
<tr>
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<td>0.194</td>
<td>0.211</td>
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<td>0.197</td>
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Elastic Modulus [N/mm²]

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<th>E_{test 3}</th>
<th>E_{test 4}</th>
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<th>rms</th>
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<td>12.663</td>
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<td>10.033</td>
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Appendix 1 page -30-
Stone Wool, lamella (50/80)

Ageing condition: 50°C  80% RH
SID:  4.4

Test: tension perpendicular to face

Tension Capacity [N/mm²]

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<th>$\sigma_{\text{test } 3}$</th>
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<tr>
<td>7</td>
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Elastic Modulus [N/mm²]

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<th>$E_{\text{test } 2}$</th>
<th>$E_{\text{test } 3}$</th>
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Appendix 1 page -31-
Stone Wool, lamella (90/60)

Aging condition: 90°C 60% RH  
SID: 4.4  
Test: tension perpendicular to face

### Tension Capacity [N/mm²]

<table>
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<th>Test 2</th>
<th>Test 3</th>
<th>Test 4</th>
<th>Test 5</th>
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<th>rms</th>
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### Elastic Modulus [N/mm²]

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<th>Test 2</th>
<th>Test 3</th>
<th>Test 4</th>
<th>Test 5</th>
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<th>rms</th>
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Appendix 1 page -32-
Stone Wool, lamella (65/100)

Ageing condition: 65°C 100% RH
SID: 4.4

Test: tension perpendicular to face (F)

Tension Capacity [N/mm²]

<table>
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<th>days</th>
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<th>Test 2</th>
<th>Test 3</th>
<th>Test 4</th>
<th>Test 5</th>
<th>avg σ</th>
<th>rms</th>
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Elastic Modulus [N/mm²]

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<th>E_test 3</th>
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</tbody>
</table>

Appendix 1 page -33-
Stone Wool, lamella (50/90)

Ageing condition: 50°C 90% RH
SID: 4.4

Test: tension perpendicular to face (F)

Tension Capacity [N/mm²]

<table>
<thead>
<tr>
<th>days</th>
<th>Test 1</th>
<th>Test 2</th>
<th>Test 3</th>
<th>Test 4</th>
<th>Test 5</th>
<th>avg</th>
<th>rms</th>
</tr>
</thead>
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<td>0.084</td>
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Elastic Modulus [N/mm²]

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<th>days</th>
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<th>Test 3</th>
<th>Test 4</th>
<th>Test 5</th>
<th>avg</th>
<th>rms</th>
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<td>56</td>
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