Review: Accelerated Climate Ageing of Building Materials, Components and Structures in the Laboratory

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ABSTRACT

Building materials, components and structures have to fulfil many functional demands during the lifetime of a building. Therefore it is important to require satisfactory durability of these materials, components and structures. In fact, one single material failure may jeopardize whole components as well as structures. Unfortunately, experience shows that building products too often do not satisfy the various requirements after a relatively short period of use, i.e. the expected service life is considerably shorter than foreseen. This results in increased and large costs due to increased maintenance, extensive replacements of the specific building products and any possible consequential building damages. In addition, health hazards with respect to both risk and consequence may also become an issue. To avoid this the solution is to apply building products which have properly documented adequate and satisfactory long-term durability. That is, building products which have been subjected to appropriate accelerated climate ageing in the laboratory. This work examines the main climate exposures and how these may be reproduced in the laboratory in various ways. Thus, crucial properties of building products and their durability towards climate strains may be investigated within a relatively short time frame compared with natural outdoor climate ageing. Examples of miscellaneous climate ageing laboratory apparatuses, ageing methods and building product properties to be tested before, during and after ageing are given. A calculation method for estimating acceleration factors is also discussed. Various ageing examples are shown and discussed. A special note is made towards accelerated climate ageing of new and advanced materials being developed. Hence, this work addresses durability and the versatile and powerful application of accelerated climate ageing which is an all too overlooked field within materials science and engineering.

Keywords: *Accelerated climate ageing, Accelerated, Climate, Ageing, Building, Material, Component, Structure, Laboratory, Acceleration factor, Durability, Climate exposure factor, Climate exposure, Robust.*

CONTENT

1. INTRODUCTION

As building materials, building components and building assemblies and structures, have to fulfil many functional demands during parts of or during the whole lifetime of a building, these building products must possess a satisfactory durability with respect to several properties. However, the experience is unfortunately that many building products all too often do not satisfy the various requirements after a relatively short time of use. Lack of durability results in large and increased costs caused by increased need of maintenance, extensive replacements of the specific building products and any possible consequential building damages. Failure in the building products may also lead to increased health hazards with respect to both health risks, i.e. the chance of a health hazard to occur, and health consequence, i.e. the impact of the health hazard if it occurs. Therefore it is important to select building products which have proven and properly documented adequate and satisfactory long-term durability. This documentation is achieved either by already carried out long-term natural outdoor climate exposure or by performing appropriate accelerated climate ageing in the laboratory.

Various building products have different resistance and durability versus the miscellaneous climate exposure factors. It is important to choose robust and durable materials, or materials with an appropriate protection, as material failure may cause failure in the building components and in the worst case breakdown of the whole building construction. The durability against the climate strains has therefore direct influence on both economical and safety aspects throughout the lifetime of a building. Various strategies exist and are applied in order to protect the materials from degradation, e.g. different paints, surface treatments and impregnations for wooden products and ultraviolet stabilizers for polymers like polyethylene, polypropylene and similar.

The objective of this study is to examine and present the main climate exposures and how these may be reproduced and applied in the laboratory in various ways. Hence, crucial properties of building products and their resistance and durability towards climate strains may be studied within a relatively short time frame compared with long-term natural outdoor climate ageing. Selected examples of miscellaneous climate ageing laboratory apparatuses, ageing methods and building product properties to be tested before, during and after ageing are given. Finally and importantly, a calculation method for estimating acceleration factors is also discussed. That is, this study addresses durability of building materials, components and structures and the versatile and powerful application of accelerated climate ageing which so far has been an all too neglected or scarcely treated area within the field of materials science and engineering.

2. TIME AND ECONOMY

Natural outdoor climate ageing processes often take a long time, and when a decision to construct has been taken one can not wait for results from natural weather ageing. In order to obtain results sufficiently fast and within economical limits, the answer is then to execute accelerated climate ageing tests which comprise various climate strains and acceleration factors. Thus, one may avoid extensive building damages due to missing or too low resistance towards climate exposures. Accelerated climate ageing will then pay off with respect to both time, costs and reputation.

3. CLIMATE AGEING AND EXPOSURES

3.1. Climate Exposure Factors

Buildings are daily and throughout the whole year subjected to large and changing climate strains, e.g. see Fig.1. These climate strains may be divided into the following climate exposure factors:

- Solar radiation, i.e. ultraviolet (UV), visible (VIS) and near infrared (NIR) radiation.
- Ambient infrared (IR) heat radiation (the resulting elevated temperature increases the rate of chemical degradation reactions, and also the rate of growth of rot and fungus up to limiting temperatures).
- High and low temperatures.

- Temperature changes/cycles (relative temperature movements between different materials, number of freezing point passes during freezing/thawing).
- Water, e.g. moisture, relative air humidity, rain (precipitation) and wind-driven rain.
- Physical strains, e.g. snow loads.
- Wind.
- Erosion (also from above factors).
- Pollutions, e.g. gases and particles in air.
- Microorganisms.
- Oxygen.
- Time (determining the effect for all the factors above to work).

Some of these climate exposure factors will be considered further in the following sections. It should be noted that several and varying combinations of the climate exposure factors will occur, and the total climate strain may be substantially larger than the added sum of the single exposure factors. It should be noted that although most people would consider the harsh and heavy precipitation downfall in the right photo in Fig.1 as the hardest climate, that is not necessarily the case as the strong solar radiation exposure depicted in the left photo in Fig.1 could lead to severe building deterioration on the exterior building surface due to photodegradation and hence with possible consequential damages. I principle, what should be considered as the most severe climate, does then not only depend on the climate itself, but also on the actual building product with its resistance and durability versus various climate exposure conditions. In Fig.2 there is shown a building finally succumbing to the climate strains through several decades and falling down due to poor and no maintenance during the last decades leading to severe and irrecoverable structural damages.

Figure 1. Buildings are subjected exposed to large and changing climate strains throughout their lifetime. Photos: Samfoto (left) and Scanpix (right) (Lisø and Kvande 2007).

Figure 2. An example of a building (left) being subjected to climate strains during several decades before finally falling down (right) due to severe structural damages. It is two years between the left and right photo.

An example of natural outdoor climate ageing testing of painted wooden samples is shown in Fig.3. During selection of building materials and components it is of major importance to choose the ones which will endure the climate strains they will be subjected to during their anticipated service life. So how should this be accomplished without having to test the materials and components throughout their whole lifetime?

Figure 3. Natural outdoor climate ageing testing of painted wooden samples.

The solution is to carry out accelerated climate ageing in the laboratory. Thus, one will obtain results within a much shorter time frame than a natural outdoor climate ageing. In addition, in laboratory one may in principle control all chosen climate exposure factors, which of course is not possible in an outdoor environment, i.e. we do not control the (natural) weather. Nevertheless, it should be noted that climate exposure in the laboratory does not cover all exposures and their interactions which take place in a natural outdoor climate ageing with real weather conditions. Therefore, care has to be taken when performing accelerated climate ageing in laboratory, both with respect to the actual test procedures and the interpretation of the results. More general literature concerning photodegradation of polymers may be found in Kumar et al. (2009), Pospíšil et al. (2006), Rånby and Rabek (1975) and Rabek (1995, 1996), whereas Evans (2009) gives a review of the weathering and photostability of modified wood. An extensive survey report on accelerated laboratory test procedures has recently been carried out by Daniotti and Cecconi (2010).

3.2. Solar Radiation and Photodegradation

Solar radiation is one of the main climate exposure factors by which many building materials may be affected and even severely damaged. The solar radiation at the earth's surface is roughly located between 290 nm and 3000 nm (0.29 μm and 3.0 μm, respectively), see Fig.4 for various solar radiation distributions. The ultraviolet (UV) radiation has wavelengths below 380 nm, the visible (VIS) light lies between 380 nm and 780 nm and the near infrared (NIR) radiation ranges between 780 nm and 3000 nm. Almost half of the solar energy is located in the NIR region. The UV radiation is further divided into the three subregions UVA (320-380 nm), UVB (280-320 nm) and UVC (100-280 nm), where the actual wavelength borders may have small variations in the literature (e.g. 315 nm as the border between UVA and UVB instead of 320 nm). Above 3000 nm, and not part of the direct solar radiation, lies the thermal radiation called infrared (IR) radiation, which all materials radiate above 0 K (peak at around 10 μm at room temperature).

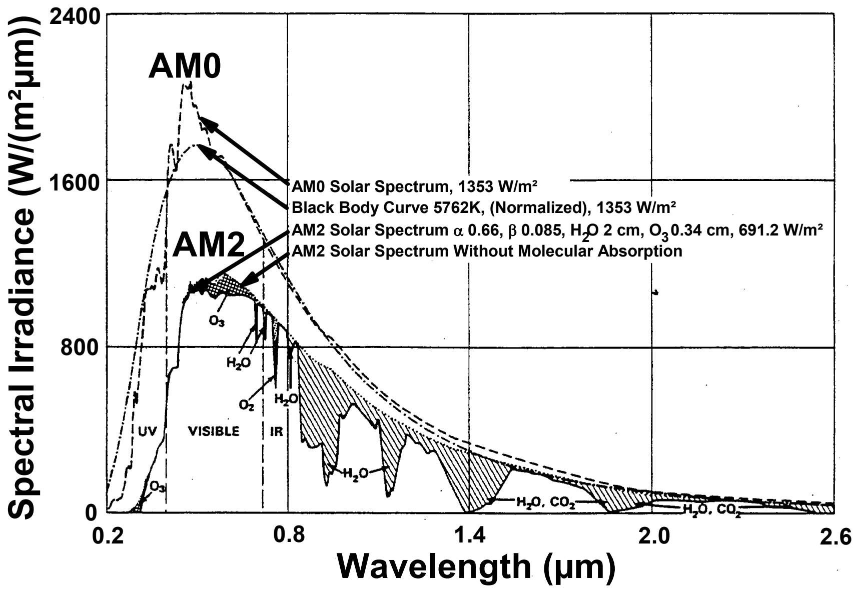


Figure 4. The solar radiation distribution, comparing the AM0 (outer space) and AM2 (at the earth's surface, the sun 30° above the horizon) spectra. The AM2 spectrum is shown both with and without molecular absorption in O_2, O_3, H_2O and CO_2. Redrawn from Fahrenbruch and Bube (1983).

Building materials, and then especially organic materials, may deteriorate as the chemical bonds are being broken by the higher energy parts of the solar spectrum, i.e. UV radiation and short wave visible light. The photodamage in materials ranges from discolouration to loss of mechanical integrity. Solar degradation of organic materials may include chemical, physical or biological reactions resulting in bond scission of organic materials with subsequent chemical transformations. These processes may involve molecular branching and crosslinking, fragmentations of molecular main chain leading to changes in molecular weight, alterations due to splitting off low molecular weight species, unsaturated carbon double bonds (C=C) and oxygenated groups.

As a reaction progress example during photodegradation, polyvinylchloride (PVC) may be chosen. During UV irradiation of PVC degradation and crosslinking processes occur, where also hydrogen chloride (HCl) and conjugated polyenes are formed. The colouration of PVC is explained by the formation of polyene structures by the following mechanism in the first step (Rånby and Rabek 1975) (refer also to Rabek 1995):

$$\text{-CH}_2\text{-CH(Cl)-CH}_2\text{-CH(Cl)- + h}\nu \rightarrow \text{-CH}_2\text{-}\dot{\text{C}}\text{H-CH}_2\text{-CH(Cl)- + }^{\bullet}\text{Cl} \quad (1)$$

$$\rightarrow \text{-CH}_2\text{-}\dot{\text{C}}\text{(Cl)-CH}_2\text{-CH(Cl)- + }^{\bullet}\text{H} \quad (2)$$

$$\rightarrow \text{-CH}_2\text{-CH(Cl)-}\dot{\text{C}}\text{H-CH(Cl)- + }^{\bullet}\text{H} \quad (3)$$

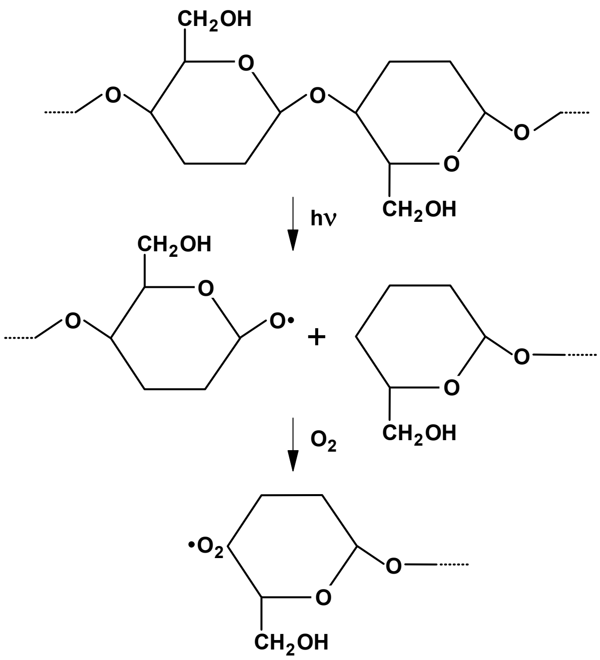
where hν denotes the photon energy of the irradiation (Planck constant multiplied with photon frequency). Furthermore, the most probable second step, which is responsible for the formation of an isolated unsaturated bond in the main carbon chain, is the chlorine radical attack on the residual macroradical (Rånby and Rabek 1975) (refer also to Rabek 1995):

$$\text{-CH}_2\text{-}\dot{\text{C}}\text{H(Cl)-CH}_2\text{-CH(Cl)- + •Cl} \rightarrow \text{-CH}_2\text{-CH=CH-CH(Cl)- + HCl} \tag{4}$$

Generally, it is agreed that the shown dehydrochlorination is a ”zipper” typereaction, where the yellow colouration requires a minimum of seven conjugated double bonds in a sequence (Rånby and Rabek 1975). In general, the photodegradation of chlorinated polymers, e.g. PVC, results in formation of chlorinated polyene sequences according to the following reaction equation (Rabek 1996):

$$\text{-CH(Cl)-CH(Cl)- + h}\nu \rightarrow \text{-(C(Cl)=CH)}_n\text{- + nHCl} \tag{5}$$

As wood is a commonly used building material, and thereby also exposed to photodegradation by the sun, we will in the following show an example of solar deterioration of cellulose. The actual composition of the photodegradation products depends on the cellulose type, where the following reaction mechanism for the primary processes during photodegradation of cellulose has been proposed (Rånby and Rabek 1975) (refer also to Rabek 1995):



(6)

The photodegradation mechanism is influenced by thermal degradation, mechanochemical degradation, physical ageing and oxidation processes. If the single photon energy E of the solar radiation given by

$$E = h\nu = hc/\lambda \tag{7}$$

where h denotes the Planck constant ($6.63 \cdot 10^{-34}$ Js), ν the photon frequency, λ the photon wavelength and c the light velocity ($3.00 \cdot 10^{8}$ m/s), is larger than the chemical bond energy of the specific material, then the photodegradation processes may start. That is, reorganization of Eq.7 yields:

$$\lambda_{threshold} = hc/E_{threshold} \tag{8}$$

where $\lambda_{threshold}$ and $E_{threshold}$ denote the threshold photon wavelength and energy, where wavelengths below and energies above, will break the actual chemical bond, respectively, e.g.

367 nm and 327 kJ/mol for C-Cl. The exact composition and structure of the various materials on an atomic level will determine the exact photon energy required to break up the chemical bonds, e.g. one or more hydrogen atoms bonded to the same carbon atom as the chloride atom in the example above, may increase the bond energy, i.e. CH_3-Cl (343 kJ/mol) has a larger bond energy than C-Cl (327 kJ/mol). Impurities in the materials may also be responsible for absorption of light at higher wavelengths.

Note that there is in some cases actual desireable to have polymers and other materials which will deteriorate after some specified time, i.e. materials with controlled lifetimes, in order to reduce the waste problem and lower the negative environmental impact. Nevertheless, usually for building products and building applications it is desired to have long-time endurable plastics and building materials, where proper care must be taken to ensure the best choice of materials and protection system.

For further details and various photodegradation reactions it is referred to the literature, e.g. work carried out by Tylli et al. (1989), Gerlock et al. (1998), Croll and Skaja (2003), Jelle et al. (2007, 2008bc) and the comprehensive studies by Rånby and Rabek (1975) and Rabek (1995, 1996). A solar material protection factor (SMPF) and a solar skin protection factor (SSPF) are introduced and defined by Jelle et al. (2007) in order to measure and calculate the capability of glass to protect indoor materials and human skin from degradation caused by solar radiation. The effects of climate change and UVB on materials are studied by Andrady et al. (2003). For several more examples of photodegradation pathways it is referred to the studies by Pandey and Vuorinen (2008a) and Wochnowski et al. (2005), of wood and poly(methyl methacrylate) (PMMA), respectively.

During the execution of accelerated climate ageing it is of vital importance not to cause any changes or chemical reactions in the materials and components which will not occur during a natural outdoor ageing process. That is, by performing an accelerated climate ageing test it is mandatory that only processes that also would have taken place during outdoor climate ageing are initiated and accelerated. For example, UV radiation with shorter wavelengths than exist in natural solar radiation at the earth's surface is not to be applied in accelerated climate ageing apparatuses, as the short wave UV radiation may induce degradation and chemical reactions that would never occur in nature. In fact, some earlier accelerated climate ageing apparatuses applied too large amounts of UVB radiation (280-320 nm) with too short wavelengths, i.e. too high-energy photons.

3.3. Elevated Temperatures

As mentioned above the solar radiation may initiate a photodegradation. The chemical degradation processes which then are started will have exponentially increasing kinetic reaction rates with respect to increasing temperatures (Arrhenius relationship, see Eq.10). For example, the increase in chemical reaction rate will be much larger by increasing the temperature from 60ºC to 70ºC than increasing from 30ºC to 40ºC, even if the increase in temperature is 10ºC in both cases (see e.g. Fig.5).

A higher ageing temperature is therefore causing a higher reaction rate for the ageing processes and thus leading to an acceleration of the climate ageing. A high acceleration factor does then imply a shorter test period. However, it is important to not expose test samples towards conditions or strains, in this case temperatures, which may induce reactions which never will take place during natural outdoor climate ageing. For ageing of various polymers accelerated ageing temperatures are therefore often chosen between 60ºC and 70ºC. More detailed discussions concerning accelerated degradation tests at elevated temperatures may be found in Meeker et al. (1998).

3.4. Freezing and Thawing Cycles

Repeated freezing and thawing of building materials and components containing water may cause large degradation due to frost weathering during water to ice volume expansion, both at a macro and micro scale. Especially in climates like e.g. the Nordic climate, which experience an extreme number of freezing point passages during winter, it is of uttermost importance to test the resistance towards these freezing/thawing cycles.

3.5. Water and Wind-Driven Rain

Water in various states, e.g. free water, relative air humidity, water vapour condensation, precipitation and wind-driven rain, will often take part in the degradation of the building materials and components. Both dissolution reactions and dilutions, mechanical degradation and erosion, freezing/thawing cycles, temperature gradients and similar may contribute to this degradation.

3.6. Other Exposure Factors and Synergy Effects

It is not within the scope of this article to treat in detail all the various climate exposure factors (e.g. as mentioned in the list in section 3.1). That is, as an example, although important, corrosion (of metal) studies are not part of this work, e.g. corrosion of reinforcement steel in concrete structures..Nevertheless, several of the factors important in corrosion investigations are also treated with regard to these factors as general climate exposure factors, e.g. elevated temperatures and water exposure. In this respect it could also be mentioned that the natural sea water coastal zone will normally be a much more corrosive environment than the 3 wt% NaCl artificial sea water often used in laboratory experiments, e.g. due to many other ions and particle substances in natural sea water exposure environment. The neglect of such issues has also led to downfall of large building parts in swimming pool centres located so they are using sea water in some of their pools, where stainless steel parts of a not high enough quality have corroded.

In addition to the above mentioned combined influence of several ageing agents in a sea water environment, synergy effects may also be found among other exposure factors and ageing processes. As an example, solar radiation, water erosion and ingress, and freezing/thawing cycles may work together to continously uncover and lay open fresh material on the surface to be degraded in a never-ceasing ageing process.

Various pollution agents, e.g. gases and particles in air, and miscellaneous microorganisms, are also part of the total climate exposure during natural outdoor ageing, and may be important to several ageing and deterioration processes, e.g. fungi growth on building products of wood (see examples in section 8). However, these factors are normally not reproduced in the laboratory, and will not be treated more in detail in this context as the main focus here is the accelerated climate ageing of building products in the laboratory.

4. ACCELERATION FACTOR

In order to estimate the required ageing time in the climate ageing apparatus, thus relating the accelerated climate ageing to the desired service lifetime of the product, one may calculate so-called acceleration factors.

The higher UV intensity (W/m^2) and total energy (kWh/m^2) in the ageing apparatus, the higher the acceleration factor for the climate ageing will be. The UV acceleration factor AF_{uv} may be calculated as directly proportional to the ratio between the total UV energy in the laboratory ageing apparatus Φ_{lab} and the natural outdoor ageing Φ_{nat} for a given time period:

$$AF_{uv} = \Phi_{lab} / \Phi_{nat} \tag{9}$$

The above Eq.9 is is valid as long as one may assume that all the UV radiation contributes to initiate degradation reactions, in addition to an equal spectral distribution for artificial and natural UV radiation, which naturally is never completely fulfilled.

The chemical degradation processes increase exponentially with increasing temperature (Arrhenius equation). A temperature acceleration factor AF_{temp} may then be calculated as the ratio between the reaction rate in the laboratory ageing apparatus k_{lab} and the natural outdoor ageing k_{nat}:

$$AF_{temp} = k_{lab} / k_{nat} = \frac{C_{lab} e^{-E_{lab}/(RT_{lab})}}{C_{nat} e^{-E_{nat}/(RT_{nat})}} \approx \frac{e^{-E_{lab}/(RT_{lab})}}{e^{-E_{nat}/(RT_{nat})}} \tag{10}$$

where T_{lab} and T_{nat} denote the temperature in laboratory ageing apparatus and the natural outdoor ageing, respectively. $R = 8.314$ J/(Kmol) is the gas constant. It is here assumed that the pre-exponential factor C is temperature independent which gives $C_{lab} \approx C_{nat}$. Furthermore, it is also assumed that the activation energy E is temperature independent and set to $E_{lab} = E_{nat} = 70$ kJ/mol, which value is applied in the graphical plots in Fig.5.

In a simplified model one may assume that the total acceleration factor AF_{tot} equals the product of AF_{uv} and AF_{temp}:

$$AF_{tot} = AF_{uv} \cdot AF_{temp} = \frac{\Phi_{lab}}{\Phi_{nat}} \cdot \frac{e^{-E_{lab}/(RT_{lab})}}{e^{-E_{nat}/(RT_{nat})}} \tag{11}$$

which is visualized in Fig.5 where $AF_{uv} = 2$ is chosen as an example. These calculations are of course a strong simplification. The other climate factors as mentioned above, e.g. water, will influence AF_{tot}. The acceleration factor is strongly dependent upon the chosen reference level, i.e. the natural outdoor ageing comparison exposure level, e.g. T_{nat}. In order to determine the real AF_{tot} one may strictly not base the calculations upon annual or daily values for Φ_{nat} and T_{nat} (k_{nat}), but on the contrary rather perform calculations with short time intervals which hence are integrated. It is important to note that a natural outdoor exposure time period at a high temperature and an equal natural outdoor exposure time period at a low temperature will result in a substantially higher reference temperature than the average temperature due to the exponential increase in reaction rate with increasing temperature (Eq.10 and Fig.5). Nevertheless, the simplified model may be applied for various mutual comparisons by accelerated climate ageing in laboratory. One also has to compare the laboratory results with outdoor tests in natural climate. Typical calculated values for AF_{tot} are often ranging between 5 to 250. It should be noted that even if AF_{uv} may be rather low (e.g. $AF_{uv} = 2$ in Fig.5) and AF_{temp} much higher, the influence of AF_{uv} might still be large on AF_{tot} due to the multiplication as given in Eq.11, e.g. $AF_{uv} = 2$ in Fig.5 actually doubles AF_{tot}.

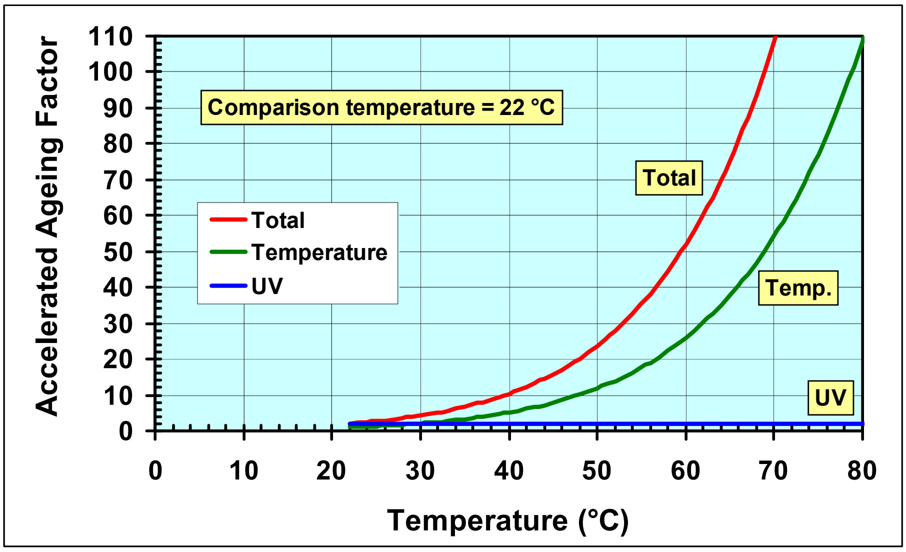


Figure 5. Calculated UV, temperature and total acceleration factor vs. temperature from Eqs.9-11, respectively.

5. AGEING APPARATUSES AND METHODS

A series of accelerated climate ageing apparatuses, which are subjecting test samples with various climate exposures, are utilized in the laboratory according to different ageing methods and standards. The building materials and components have to withstand these climate exposures in order to endure the naturally occuring climate strains, and thus be able to avoid damages in prospective applications. Some of these ageing apparatuses and methods will be mentioned within this context to illustrate their possibilities.

In Fig.6 there is shown accelerated climate ageing of wooden samples with various surface treatments in a vertical climate simulator according to Nordtest Method NT Build 495 (2000), including a principial drawing of the apparatus. In this test equipment the samples are subjected in turns to four different climate zones, that is, one UV and IR irradiation zone (black panel temperature of 63ºC), one water spray zone (15 $dm^3/(m^2h)$), one freezing zone (-20ºC) and thawing in one indoor laboratory climate zone. Depending on the choice of type of UV tubes, the UV intensity may be chosen at different levels, e.g. for one specific set of UV tubes the UVA and UVB intensities are averaged to 15 W/m^2 and 1.5 W/m^2, respectively. The exposure time is 1 hour in each climate zone in the above given sequence. For further details it is referred to the test method (NT Build 495). Note that this specific vertical climate simulator is a special non-commercial accelerated climate ageing apparatus fulfilling the requirements of a specific ageing method (i.e. NT Build 495).

Another example of a special non-commercial accelerated climate ageing apparatus is shown in Fig.7, which is a combined horizontal UV, temperature and water spray ageing apparatus, in this case shown in the open position with the wooden samples. This horizontal ageing apparatus is typically applied for testing of roofing products according to EN 1297 (2004).

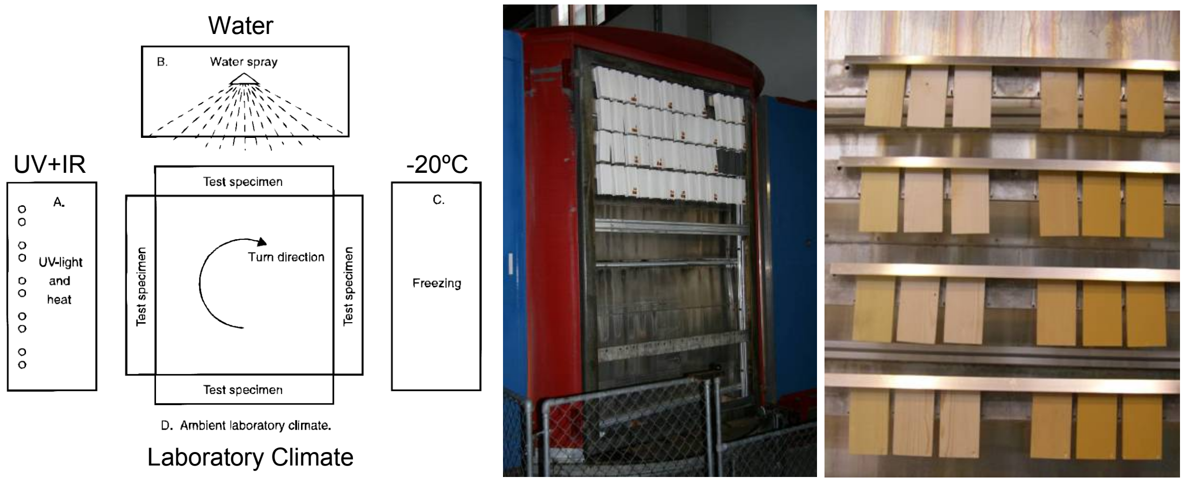


Figure 6. Accelerated climate ageing of wooden samples with various surface treatments in a vertical climate simulator according to Nordtest Method NT Build 495 (2000) with a principial drawing of the apparatus to the left.

Figure 7. Accelerated climate ageing of wooden samples in a combined horizontal UV, temperature and water spray ageing apparatus. Tests are typically performed on roofing products according to EN 1297 (2004).

Commercial climate ageing apparatuses are also available, where a QUV apparatus (UV tubes) Weathering Tester Horizontal Option with Ponding and Water Spray (The Q-Panel Company, Cleveland, Ohio, USA), Atlas SC600 MHG Solar Simulator (metal halide global lamp) and an Atlas Suntest XXL+ (xenon lamp) are shown in Fig.8. These apparatuses may be run according to different test methods and standards.

The choice of light source for the accelerated climate ageing tests may be crucial. Various UV tubes with energy peaks shifted towards lower or higher wavelengths in the UV region may be purchased and applied. Metal halide (MH) lamps simulate the solar spectrum at the earth's surface, with the global version (MHG) closest to the solar spectrum. Xenon lamps are reckoned as the lamps able to closest simulate the solar radiation at the earth's surface. For example, if a photovoltaic solar cell is subjected to accelerated climate ageing with simultanously measurements of the solar cell characteristics (e.g. open circuit potential, short circuit current, maximum output power, fill factor and efficiency), xenon or metal halide global lamps have to be used, i.e. UV tubes can not be applied in such a case. For some applications special filters are employed, e.g. in order to simulate solar radiation through window glass panes.

Figure 8. Three commercial accelerated climate ageing apparatuses with different light sources, i.e. QUV apparatus (UV tubes), Atlas SC600 MHG Solar Simulator (metal halide global lamp) and Atlas Suntest XXL+ (xenon lamp) from left to right, respectively.

As another example of accelerated climate ageing, Fig.9 shows painted cotton canvas samples before and after sun and temperature ageing in the Atlas SC600 MHG Solar Simulator climate chamber with a 2500 W MHG lamp as light source. Temperature and relative air humidity (RH) were held constant at 50ºC and 80 % RH for 24 h per day, respectively. The samples were placed in the climate chamber with a distance of approximately 55 cm from the climate chamber interior glass ceiling to the sample surface, where the solar radiation intensity is reported to be 1200 W/m^2 at 100 % lamp power intensity, and thus 600 W/m^2 applying a 50 % physical metal grid filter which is the case for the ageing of these painted cotton canvas samples. As seen from the photos in Fig.9, the blue samples changes from dark blue to pale blue during the ageing.

Continous solar exposure in the solar simulator with the conditions given above yields a total solar exposure of about 311.04 MJ/m^2 during 6 days (6 x 24 hours). This value may be compared with EOTA (2004) reference values between 3.4-6.6 GJ/m^2 per year, which corrected/adjusted for a temperature factor (0.67) become 2.3-4.4 GJ/m^2 per year. The temperature factor 0.67 is applied due to the fact that not all solar irradiation is occurring at high summer temperatures and the solar irradiation will therefore be less damaging for the exposed surfaces at lower temperatures. The value 0.67 x 5 GJ/m^2 per year = 3.35 GJ/m^2 per year has been chosen as a reference value where an exposure $<$ 5 GJ/m^2 per year and $<$ 22ºC (3.35 GJ/m^2 temperature corrected) represents a moderate climate, whereas an exposure $\geq$ 5 GJ/m^2 per year and/or 22ºC (3.35 GJ/m^2 temperature corrected) represents a severe climate with respect to solar radiation exposure. The temperature of 22ºC refers to a reference average temperature for the warmest month during the year according to the EOTA (2004) classification. A solar exposure of 5 GJ/m^2 per year

(3.35 GJ/m^2 temperature corrected) corresponds to a solar radiation exposure in northern Spain/Italy.

Ageing in the solar simulator at 50ºC and 600 W/m^2, and compared to 22ºC as a reference temperature, yields a temperature acceleration factor of 11.84 (Eq.3), and a combined total sun and temperature acceleration factor of (365/6) x (0.31104/3.35) x 11.84 ≈ 5.65 x 11.84 ≈ 66.9 ≈ 67 (Eq.3 and Eq.4). Summarized, we may say that 6 days (6 x 24 hours) in the solar simulator corresponds to somewhat more than 1 year (about 400 days) outdoor exposure compared to the applied reference value, where the process is accelerated with respect to both higher solar exposure and an increased temperature. It should be noted that this combined acceleration factor is a calculated number which can not be directly compared with natural outdoor conditions (among other factors influences from moisture, various pollutions, temperature motions and freezing/thawing cycles are not considered).

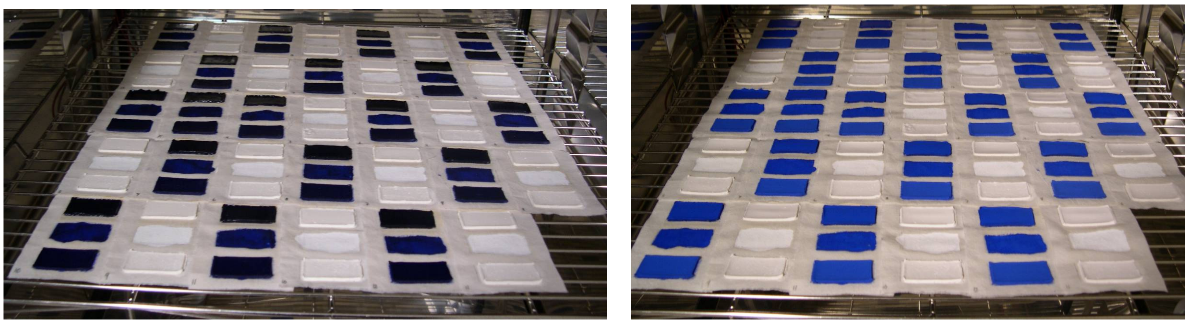


Figure 9. Accelerated climate ageing of painted cotton canvas samples in the Atlas SC600 MHG Solar Simulator. Before ageing to the left and after ageing to the right.

Several weathering or accelerated climate ageing methods and standards exist, e.g. ASTM G23-81 (1981), ASTM G24-87 (1987), ASTM G26-84 (1984), ASTM G53-84 (1984), EN 927-3 (2000), EN 927-6 (2006), EN 1296 (2001), EN 1297 (2004), EN ISO 4628-1 (2003), EN ISO 4892-1 (2000), EN ISO 4892-2 (2006), EN ISO 4892-3 (2006), EOTA (2004), NT Poly 161 (1993), NT Build 216 (1982), NT Build 228 (1992), NT Build 229 (1989) and NT Build 495 (2000); just to mention a few examples (see reference list for further details). Pure heat or temperature accelerated ageing tests are also commonly carried out, e.g. according to EN 1296 (2001). Also note the earlier mentioned comprehensive work by Daniotti and Cecconi (2010) on accelerated laboratory test procedures.

Accelerated ageing and photodegradation by UV lasers are also in use, e.g. in studies of wood surfaces. The application of UV lasers may decrease the exposure time drastically, e.g. from weeks and days to hours and minutes. In addition, when using UV lasers the wavelength and hence the photon energy (Eq.7) may be controlled very accurately during irradiation of the samples. Thus, more exact information and correlations between the exposed material samples with various chemical bond energies, solar radiation exposure conditions, and photochemical and photodegradation pathways, may be acquired. One possible outcome of such studies may be various ways of protecting different materials against solar radiation. Several authors have been applying UV lasers in various irradiation studies of wood and polymer materials, e.g. Karlitschek et al. (1995), Pandey and Vuorinen (2008ab), Papp et al. (2005) and Wochnowski et al. (2005).

6. EVALUATION BEFORE, DURING AND AFTER AGEING

Various properties of the building materials and components should be tested and evaluated before, during and after completed accelerated climate ageing. Specific requirements are chosen for these properties in order to avoid building damages. Examples of various properties to be evaluated according to specific criteria may be:

- **Visual evaluation**
  - E.g. according to EN ISO 4628-1 (2003)
  - Light microscope
  - Electron microscope, e.g. scanning electron microscope (SEM) and transmission electron microscope (TEM)
- **Colour measurements**
  - Colour coordinates L, a, b, ΔE, yellowing E313, gloss 60°, etc.
- **Various mechanical tests**
  - Tensile strength
  - Compression strength
  - Shear strength
  - Elongation
  - Resistance towards impact
  - Etc.
- **Adhesive strength**
  - Adhesive strength of surface coatings to substrates
  - Adhesive strength of granulates
  - Etc.
- **Water tightness**
- **Water vapour permeability**
- **Flexibility at low temperature**
- **Elemental analysis, often by energy dispersive spectroscopy (EDS) (by x-ray) most commonly found in scanning electron microscopes (SEMs)**
- **Transmittance, absorbance and reflectance**
  - Ultraviolet, visible and near infrared (UV-VIS-NIR) spectrophotometry
  - Fourier transform infrared (FTIR) spectroscopy
  - Direct (specular) and diffuse reflected radiation (UV, VIS, NIR and IR)
  - Atomic absorption spectroscopy (absorption of light by free atoms in gas state)
  - Etc.
- **Surface analysis**
  - Various tools including some of the above mentioned ones
  - Atomic force microscope (AFM)
  - X-ray photoelectron spectroscopy (XPS)
  - Fluorescence spectroscopy
  - Raman spectroscopy
  - Attenuated total reflectance (ATR) Fourier transform infrared (FTIR) spectroscopy
  - Etc.
- **Material characterization by FTIR analysis**
- **Etc.**

Examples of FTIR analysis and SEM studies including elemental analysis by EDS are depicted in section 7 and section 8.2, respectively. Several visual observations are depicted in section 8. Prominent colour changes before and after accelerated solar radiation exposure ageing are shown in Fig.9. To investigate possible correlations between specific properties during ageing may often prove to be very informative and helpful, where one example may be chemical changes studied by FTIR analysis and various mechanical properties like e.g. tensile and compression strength.

Colour measurements involve the determination of among others the colour coordinates L, a and b in a three-dimensional colour space, where higher positive values denote a more light colour (on a white-black scale, i.e. higher luminance), a more reddish colour (on a red-green scale) and a more yellowish colour (on a yellow-blue scale), respectively. A higher positive Y E313 yellowing value designates a more yellowish colour. Furthermore, a higher G 60º gloss value denotes a more glossy (shiny) material. One may also calculate a colour difference ΔE as:

$$\Delta E = \sqrt{(\Delta L)^2 + (\Delta a)^2 + (\Delta b)^2} \tag{12}$$

where $\Delta L = L_2 - L_1$, $\Delta a = a_2 - a_1$ and $\Delta b = b_2 - b_1$, where (L_2, a_2, b_2) and (L_1, a_1, b_1) represent two colours or colour coordinates in the three-dimensional CIELab colour space. Thus, the colour difference ΔE represents the distance between two colours, e.g. a colour difference between a non-aged and an aged condition. Figure 10 depicts actual colour measurements before and after accelerated climate ageing according to NT Build 495 (2000) (of the red plaster boards depicted in Fig.23), including calculation of the colour difference ΔE. See e.g. the work by Prakash et al. (2006), Prakash and Mahadevan (2008) and Rosu et al. (2010) for colour change studies of modified wood by artificial light irradiation.

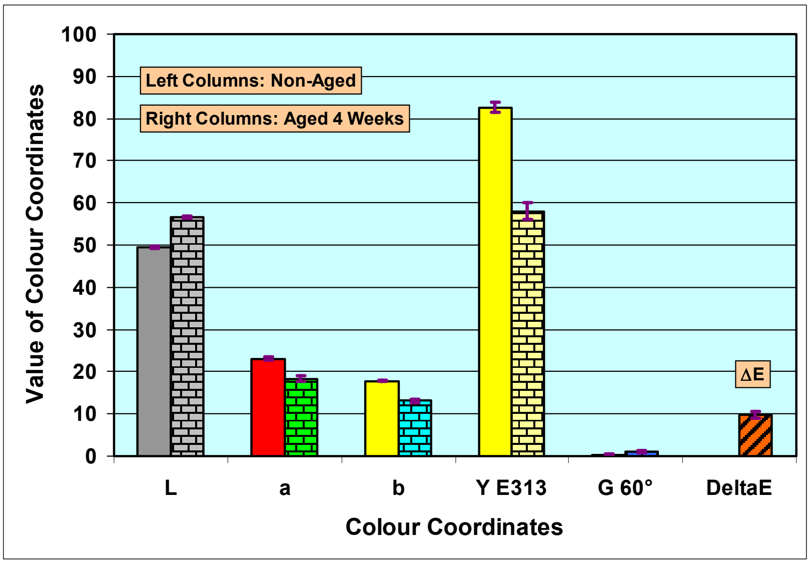


Figure 10. Colour measurements before and after accelerated climate ageing according to NT Build 495 (2000) (of the red plaster boards depicted in Fig.23). The small violet error bars on top of each column represent the uncertainty as the standard deviation of the mean with 99.73 % confidence (normal distribution), i.e. all the measured colour changes are significant.

The development of a given property with time may be difficult or impossible to predict in advance. Both large and small changes in properties may occur in the start, during and at the end of the ageing time, and the development may follow different courses and curve shapes, e.g. both linear and exponential, see various examples depicted in Fig.11. That is, if a property is measured only before and after ageing, valuable information about the ageing resistance might be lost. For example, if the measurements after ageing, corresponding to e.g. 20 years of natural outdoor ageing, demonstrate that the material or component has failed, one does not know if the product failed after only 2 years or if it in fact showed almost no degradation up to 19 years, whereas thereafter it failed rapidly. The specific property, e.g. tensile strength, will normally have requirements for a minimum (or maximum for some properties) value during the expected service life, which in Fig.11 is depicted as a horizontal red failure level line at 40 % as an example. Furthermore, depending on the required service life, it may also be of great interest to know how well above the failure level a property is able to be throughout the desired lifetime. Hence, it is concluded that in addition to measurements performed before and after ageing, it may also be beneficial to carry out different tests during the accelerated climate ageing.

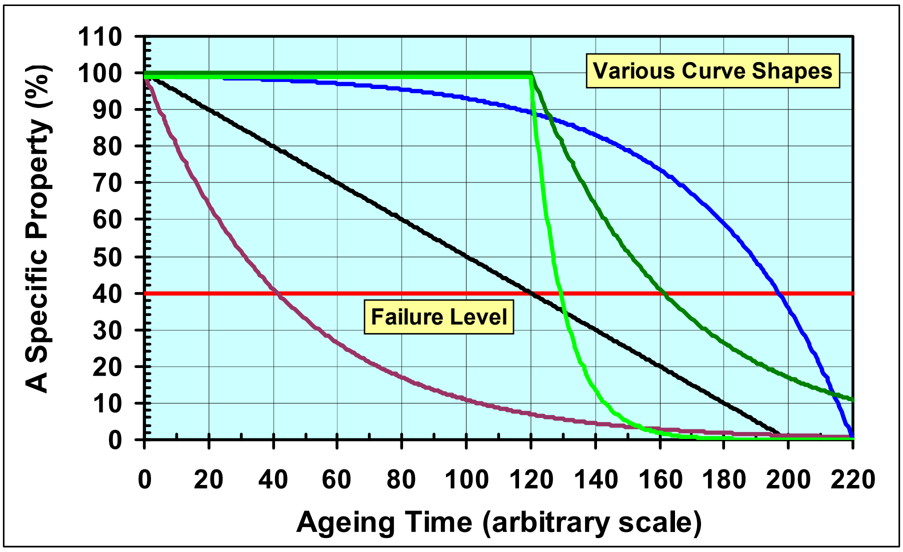


Figure 11. A graphical visualization of some examples of possible changes and development of properties during an accelerated climate ageing, depicting various curve shapes including both linear and exponential courses. In addition, a horizontal red failure level line at 40 % as an example is depicted.

7. FTIR ANALYSIS

Material characterization by Fourier transform infrared (FTIR) analysis before, during and after an accelerated climate ageing may give information about both the extent of the ageing and which degradation mechanisms are taking place. This information may then be utilized to prevent building damages. In Fig.12 and Fig.13 the FTIR analysis reveals that an oxidation of polypropylene occurs during an accelerated climate ageing with UV exposure at 50ºC in QUV apparatus (Fig.8), where the absorbance peak around 1732 cm^{-1} is attributed to carbonyl (C=O) stretching. In addition, quantitative results from a FTIR analysis may be correlated to other tests performed during an accelerated ageing experiment, e.g. tensile strength measurements. Thus, FTIR analysis may represent a powerful and insightful evaluation tool during accelerated climate ageing.

The attenuated total reflectance (ATR) technique utilized in FTIR spectroscopical investigations makes it possible in principle to measure chemical changes directly in the material surface. That is, the ATR technique requires none or only minor sample preparations, saving both time and enabling the study of materials in a pristine condition. Thus, in several cases, the ATR technique will be superior compared to more traditional FTIR techniques carried out by running transmission spectra through material samples dissolved in a suitable liquid or pressed into a thin KBr pellet. The actual measurements on the polypropylene sample with the ATR accessory for the FTIR spectra depicted in Fig.12 and Fig.13 is shown in Fig.14. Some selected applications of the FTIR and ATR-FTIR techniques on various building materials or related materials studying miscellaneous degradation, weathering and accelerated ageing processes may be found in work carried out by Anderson et al. (1991ab), Backa et al. (2001), Colom et al. (2003), Commereuc et al. (1997), Corti et al. (2010), Croll and Skaja (2003), Ding et al. (2006), Faix et al. (1991), Forsthuber and Grüll (2010), Genestar and Palou (2006), Gerlock et al. (1998), Gulmine and Akcelrud (2006), Humar et al. (2006), Jebrane et al. (2009), Jelle et al. (2008abc), Jelle and Nilsen (2011), Jelle (2011a), Jelle et al. (2012b), Kim et al. (1994), Marengo et al. (2005), Mohebby (2005), Naumann et al. (2005), Oliani et al. (2007), Pandey and Pitman (2003, 2004), Pandey (2005), Pandey and Vuorinen (2008a), Pandey et al. (2009), Prakash et al. (2006), Prakash and Mahadevan (2008), Rosu et al. (2010), Schmitt and Flemming (1998), Stark and Matuana (2004), Sudiyani et al. (2003), Wang et al. (2002), Wochnowski et al. (2005), Woo et al. (2006ab) and Yamauchi et al. (2004).

The FTIR material characterization depicted in Fig.12 and Fig.13 was carried out with a Thermo Nicolet 8700 FTIR spectrometer with a Smart Orbit accessory, i.e. a horizontal attenuated total reflectance (ATR) accessory (single reflection) with a diamond crystal, in the wavelength range 4000 cm^{-1} (2.5 μm) to 400 cm^{-1} (25 μm) in an atmosphere with minimalized CO_2 and H_2O content through purging by a Parker Balston 74-5041 FTIR Purge Gas Generator (Jelle and Nilsen 2011). Each FTIR spectrum presented is based on a recording of 32 scans at a resolution of 4 cm^{-1}. In order to ensure satisfactory contact between the ATR diamond crystal and the sample, three or more FTIR spectra were recorded at various locations on the sample. The polymer surfaces are relatively hard, which complicates accurate quantitative measurements (height of absorbance peaks) due to varying contact with the ATR crystal for the different samples. Air between sample and ATR crystal results in a weaker absorbance signal. Unless other conditions indicate otherwise (e.g. inhomogenities, impurities, etc.), the FTIR curves with the largest absorbance peaks represent the most correct measurements on one and the same sample with equal ageing time, and hence these curves are chosen or assumed as the most correct ones. Qualitative measurements (location of absorbance peaks at wave numbers) do not represent a problem as long as the contact area is large enough to ensure a sufficient strong measurement signal. The FTIR spectra given in this work have not been ATR corrected, neither with respect to penetration depths nor absorbance band shifts, which both are dependent on the refractive indices of the sample and the ATR crystal (diamond in this case) and the angle of incident radiation. The penetration depth is in addition also dependent on the radiation wavelength, and increases with increasing wavelength (decreasing wave number). That is, non-corrected ATR spectra have much stronger absorbance bands at longer wavelengths (smaller wave numbers) than at shorter wavelengths (larger wave numbers). Note that it should always be stated if an ATR-FTIR spectrum has been ATR corrected or not, e.g. important during computerized database spectra comparison searches.

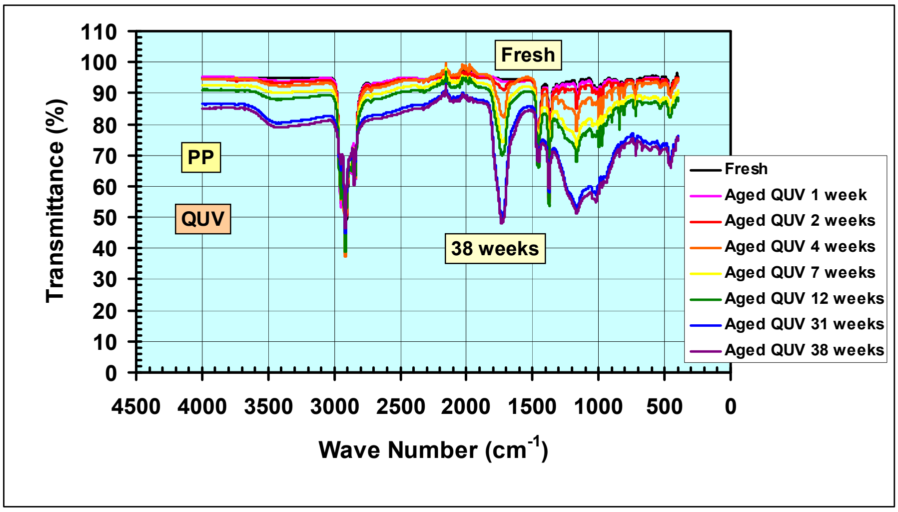


Figure 12. FTIR transmittance vs. wave number between 4000-400 cm^{-1} for polypropylene during UV exposure at 50ºC (Jelle and Nilsen 2011).

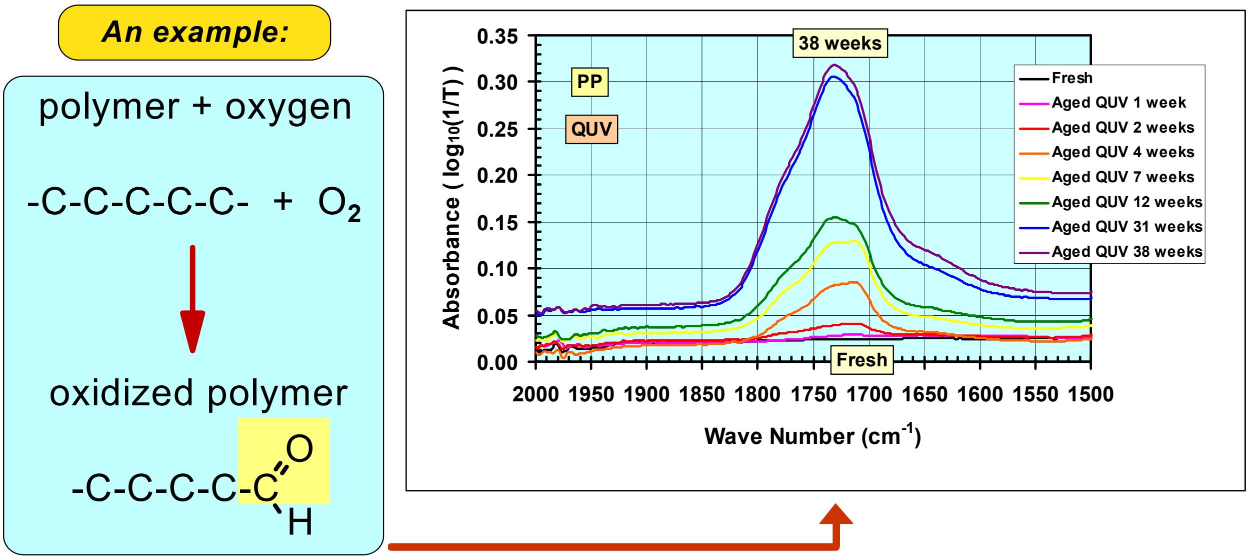


Figure 13. Accelerated climate ageing of polypropylene and corresponding FTIR analysis (excerpt from Fig.12) also depicting the oxidation of the polymer.

Figure 14. Measurements on the polypropylene sample with the ATR accessory for the FTIR spectra depicted in Fig.12 and Fig.13. To ensure proper contact between the ATR diamond crystal and the sample is crucial for quantitative evaluations. Note that the lower steel pin is only a reflection of the above steel pin in the polished mirror-like sample plate.

As the absorption of electromagnetic radiation, e.g. IR radiation, follows the Beer-Lambert law, i.e. the radiation is decreasing exponentially with the penetration depth in the actual material, it is often helpful to plot the spectra on a logarithmic absorbance scale vs. wavelength or wave number. Hence, the transmittance spectra in Fig.12 are plotted on a logarithmic absorbance scale for quantitative studies in Fig.13. Mathematically and physically it follows that a doubling of the logarithmic absorbance, also called optical density, is interpreted as a doubling of material thickness or a doubling of concentration of absorption active agents. Thus, in this case, the concentration growth of carbonyl groups (C=O) as depicted in Fig.13.

8. AGEING EXAMPLES

In addition to the ageing examples already given in the above, this section will in the following present various ageing examples with respect to both materials, components and structures. Note that material failure may lead to breakdown of various components and larger structures. That is, protection and durability at a material level will be crucial, both for traditional, state-of-the-art and beyond state-of-the-art materials, the latter ones yet to be discovered and made.

8.1. Ageing of Gasket Materials

In Fig.15 there is shown an example of a building damage case where the gasket materials for glass montage in a facade after short time did not withstand the climate exposures. To replace all the gaskets was a costly enterprise. In addition, all the facade glasses represented a health hazard both with respect to the risk and the impact of glass falling down. Such shortcomings regarding durability and resistance towards climate strains are often disclosed relatively fast in the laboratory by carrying out accelerated climate ageing.

Figure 15. An example of a building damage case where the facade glass gaskets after short time did not withstand the climate strains.

8.2. Ageing of Expanding Weather Stripping Foam

An expanding weather stripping foam is intended for application between various building component joints in the building envelope, e.g. between a window and its joints towards the wall, in order to provide a satisfactory air tightness. During construction the distance may vary in these joints, therefore it is required that the weather stripping is able to expand up to a specified thickness. This expansion capability has to be intact for a specified service life, or else the air tightness will be substantially jeopardized. Figure 16 shows an example of an expanding weather stripping which has been subjected to accelerated ageing in the laboratory, where both samples first have been aged according to NT Build 495 (2000) (UV and IR irradiation with a black panel temperature of 63ºC, water spray, freezing at -20ºC and thawing) for 15 days (15 x 24 h), while the left sample afterwards also has undergone heat ageing at 70ºC for 90 days (90 x 24 h). The samples were aged at a normal expanded condition of 12 mm, and after the ageing the sample which had been subjected to both the short-term NT Build 495 (2000) and the long-term heat ageing was only able to expand to 15 mm, while the sample which had been subjected to only the short-term NT Build 495 (2000) exposure was able to expand to 28 mm (similar to a non-aged sample).

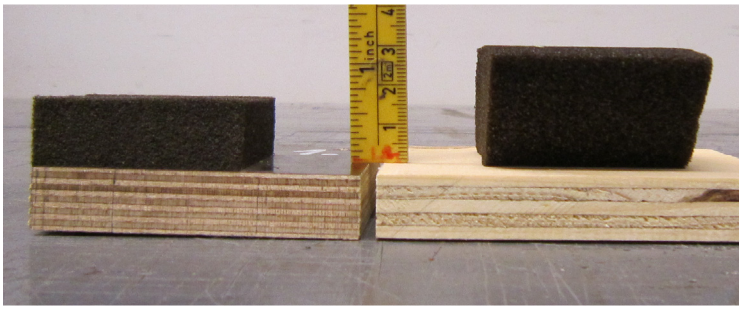


Figure 16. Expanding weather stripping foam after ageing, where the sample subjected to both the short-term NT Build 495 (2000) and the long-term heat ageing is shown to the left, and where the sample subjected to only the short-term NT Build 495 (2000) exposure is shown to the right.

FTIR spectra were recorded for both a non-aged, NT Build 495 (2000) aged and combined short-term NT Build 495 (2000) and long-term heat aged sample (Fig.17), and revealed nearly identical FTIR spectra (qualitatively similar with some minor quantitatively differences) for all three samples, i.e. no chemical changes which would have been visible in the FTIR spectra could have occurred. Hence, the FTIR spectra indicate that the weather stripping foam have not *chemically* changed significantly during the ageing. The FTIR measurement points were located approximately 5 mm from the exposed (e.g. UV) surface and into the bulk material. However, SEM disclosed the difference in ageing between the samples as depicted in Fig.18, and revealed that the matrix constituting the pore structure in the expanding weather stripping had been only partly damaged by the short-term NT Build 495 (2000) exposure, whereas it had been severly damaged by the long-term heat ageing.

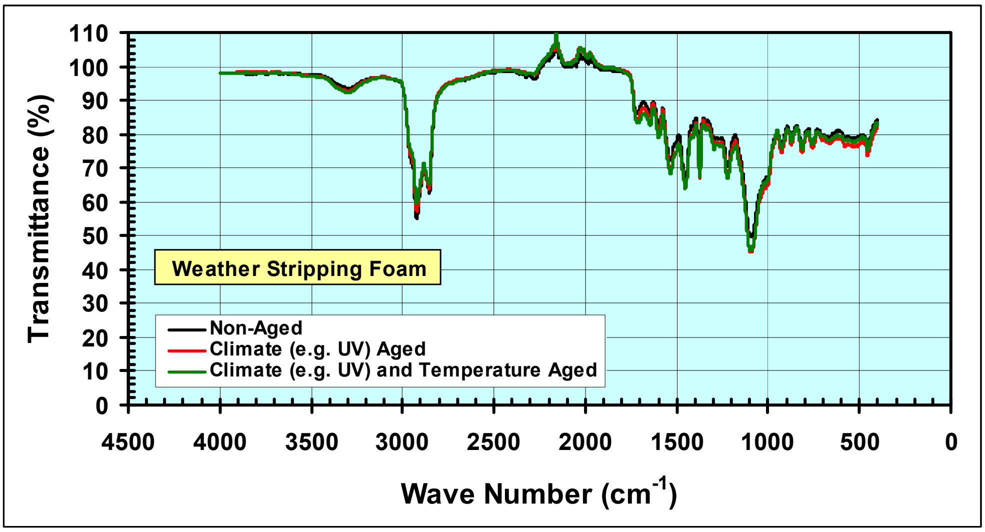


Figure 17. FTIR transmittance versus wave number between 4000-400 cm^{-1} in the bulk of the expanding weather stripping foam in non-aged and aged conditions.

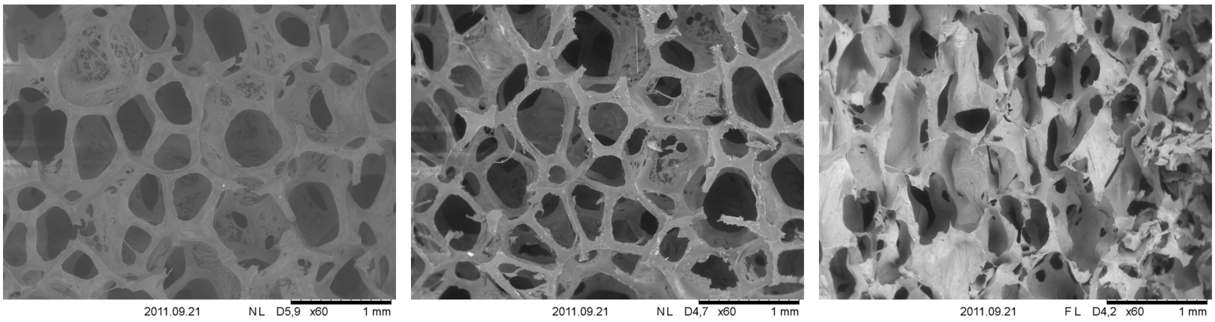


Figure 18. SEM photos (60 X magnification) of the expanding weather stripping foam, non-aged sample to the left, sample subjected to only the short-term NT Build 495 (2000) exposure in the middle, and sample subjected to both the short-term NT Build 495 (2000) and the long-term heat ageing to the right.

Closer inspection at larger magnifications with the SEM revealed some crystals in the pore matrix structure of the expanding weather stripping foam, both after the short-term NT Build 495 (2000) exposure and the long-term heat ageing. Elemental analysis through energy dispersive spectroscopy (EDS) unveiled that these crystals contained calcium (Ca) as depicted in Fig.19. It was concluded that the origin of the calcium-containing crystals stemmed from the water (tap water) spray exposure during the accelerated climate ageing according to NT Build 495 (2000). This also demonstrates that care has to be taken with respect to the water source used during accelerated climate ageing experiments.

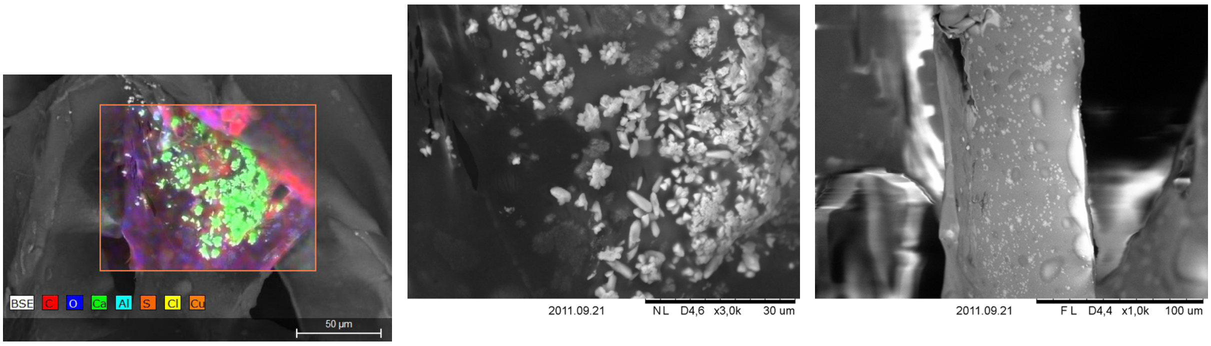


Figure 19. Elemental analysis through energy dispersive spectroscopy (EDS) to the left and SEM photos in the middle (3000 X magnification) and to the right (1000 X magnification) depicting the same area where the EDS was performed, revealing calcium-containing crystals in the pore matrix structure of the expanding weather stripping foam (after long-term heat ageing).

8.3. Ageing of Windows and Consequential Damages

Windows and other glass structures play an important role in the building envelope offering the admittance of both daylight and solar energy into the building, while at the same time giving the occupants a view to the outside and shielding them from various weather exposures like e.g. rain, snow and wind. Nevertheless, the windows may also represent weak points in the building envelope with respect to withstanding the climate exposures during several years. Hence, special care has to be taken concerning the windows. The different window materials and components and their interaction should be tested and evaluated, and also their interfaces with the rest of the building envelope.

To withstand a harsh and changing climate for a limited time period is one thing, to withstand this climate for many years and decades is a much harder task. The air- and raintightness of a window should then ideally be tested before and after a sufficient long accelerated climate ageing exposure. Unfortunately, accelerated climate ageing tests are often not carried out to the extent it should, if at all. Then, the results after some years might even be damages to the building construction beneath the window, e.g. example in Fig.20 where also the timber work was damaged.

Figure 20. Large wood rot decay and fungi growth damages in a window and the construction below caused by moisture penetration during many years. The window had not been tested versus accelerated climate ageing and raintightness.

8.4. Ageing of Composite Structures with Facade Cladding

Accelerated climate ageing of a composite structure consisting of several materials and components in a vertical climate simulator according to Nordtest Method NT Build 495 (2000) is depicted in Fig.21 and Fig.22. The composite structure included facade cladding (mortar) on facade wallboards. The ageing test revealed many cracks of different lengths, widths and depths in the painted surface, also into the mortar. Water penetrating into the structure caused the wallboards beneath the mortar surface to swell, and thereby increasing the climate exposure degradation of the composite structure furthermore. The results were used to substantially improve the weather exposure and ageing resistance of this specific building structure. Note that freezing and thawing cycles may play a crucial role in the degradation of such composite structures. Hence, the resistance of a structure towards freezing point passes during freezing and thawing is of vital importance, also with respect to the interaction between various materials and components.

Figure 21. Disclosing weak spots in a composite structure during accelerated climate ageing in a vertical climate simulator according to Nordtest Method NT Build 495 (2000).

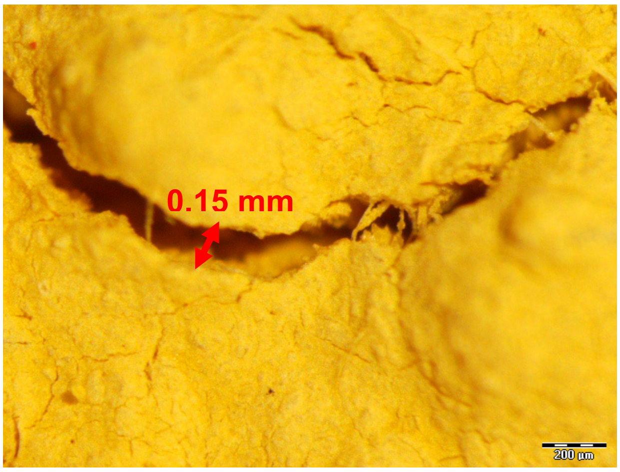


Figure 22. A closer inspection of the painted surface of the composite structure depicted in Fig.21 revealed many small cracks of different lengths, widths and depths.

8.5. Ageing of Composite Structures with Plaster Boards

Accelerated climate ageing of composite structures with two different plaster (gypsum) board types in timber frameworks was carried out in a vertical climate simulator according to Nordtest Method NT Build 495 (2000). The test was investigating any potential damages these plaster board walls could experience during weather exposure at the building site when unprotected during the construction period. The resulting front facades of the two test sections are shown in Fig.23 after 1 week and 4 weeks of accelerated climate ageing. Obviously, the red plaster boards (bottom Fig.23) withstood the climate exposure substantially better than the grey plaster boards (top Fig.23). The cardboard of the grey plaster boards was considerably damaged by the water exposure, while the red plaster boards did not experience such a damage within the same time period. Still, as seen in Fig.23 and the close-up in Fig.24, the red plaster boards were also affected by the water exposure.

In order to study the vulnerabilty of these plaster board structures with a practical installation, miscellaneous issues were addressed. Among these were various ways of fastening nail perforations, e.g. from perfect nail fastenings to less perfect nail fastenings, i.e. nails which had deliberately damaged the outer surface of the plaster boards. That is, the climate exposure resistance of these plaster board walls towards errors that are normally bound to occur at a building site was investigated. The influence of vertical plaster board joints fastened to the wooden studs with nails (at the right side of the test sections in the photos in Fig.23) and horizontal plaster board joints pieced together with horizontal plastic H-moulds (depicted in Figs.23-25) was also studied. Water was found to penetrate into the structure at the weak points like nails, H-moulds, vertical and horizontal joints.

A common principle is to block as much water from entering a building envelope as possible, and then at the same time to ensure that water which actually penetrates into the structure is drained out and away from the structure again, in addition to a general drying capability of the system. It is important not to trap water or moisture between two watertight layers. Thus, the plaster board wall investigations presented here, resulted in a discussion of applying h-shaped moulds or other variations instead of the employed H-moulds, in order to enhance the water drainage capability.

The back side of the red plaster board test section is shown in Fig.25 (left), depicting the water penetration and accumulation at the section bottom and at the horizontal joint with the H-mould. Furthermore, as seen in Fig.25 (right), fungi growth was observed on the wood sill at the back side of the grey plaster board section after 4 weeks of accelerated climate ageing. During the same time period, the back side of the red plaster board section did not experience any visible fungi growth, as the water penetration and accumulation was much less for the red than the grey plaster board section. Naturally, no fungi was observed on the front side of the test sections due to the UV radiation exposure drom the vertical climate simulator.

Figure 23. Lower parts of two different plaster board sections (grey top and red bottom) after 1 week (left) and 4 weeks (right) of accelerated climate ageing in a vertical climate simulator according to Nordtest Method NT Build 495 (2000).

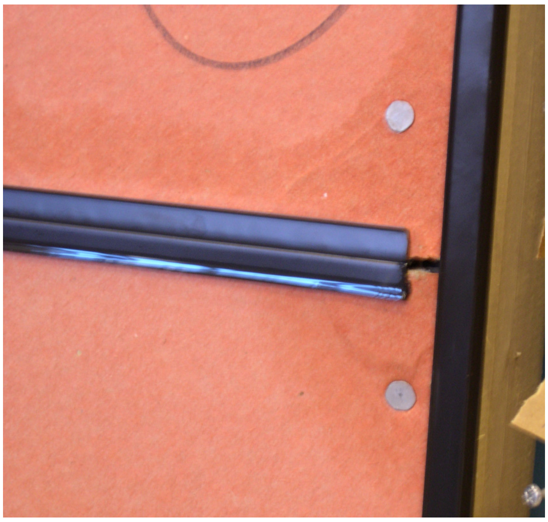


Figure 24. Close-up of red plaster board after 4 weeks of accelerated climate ageing (from Fig.23) depicting the detailed lower part of the section at horizontal H-mould in the joint between two plaster boards at the right edge.

Figure 25. Back side (left) of red plaster board section after 4 weeks of accelerated climate ageing, where the lower part of section depicts moisture located at section bottom and at horizontal H-mould in the joint between two plaster boards. Fungi growth (right) on the wood sill at the back side of the grey plaster board section after 4 weeks of accelerated climate ageing.

8.6. Ageing of New Materials and Solutions

As new materials and solutions, some of them applying nanotechnology, are being developed, there arises a need to carry out extensive testing of their ability to withstand long-term climate exposure with satisfactory durability of several crucial properties. Conducting accelerated climate ageing studies will be of vital importance for materials science and engineering advances during development, characterization and testing of these new materials and solutions. These advances will not represent a real progress in materials science unless a satisfactory performance with respect to climate ageing durability has been demonstrated.

An example of such new materials and solutions is building integrated photovoltaics (BIPV), where the developed solar cell materials and systems may beneficially be implemented into a building's exterior climate screen envelope, see Fig.26 (Solarcentury 2008). A BIPV system then also has to fulfil the requirements of a building envelope in order to deal with the different climate exposure factors, e.g. rain, air and wind tightness and various building physical aspects like heat and moisture transport (Jelle et al. 2010b, Jelle et al. 2012c). Various properties of the solar cell materials and systems have to be tested before, during and after the accelerated climate ageing, e.g. solar cell open circuit potential, short circuit current, maximum output power, fill factor (FF), efficiency, different mechanical properties and any chemical changes.

Figure 26. Example of building integrated photovoltaics (BIPV) (Solarcentury 2008).

The development of new high performance thermal insulation materials and solutions represent another group of building products which need to be tested with respect to climate ageing and different building physical properties (e.g. moisture transport and the risk of condensation) during their service life. The low thermal conductivity is a key property for these materials. The high performance thermal insulation materials and solutions of today and tomorrow include vacuum insulation panels (VIP) (Fig.27), gas-filled panels (GFP), aerogels, phase change materials (PCM), vacuum insulation materials (VIM), gas insulation materials (GIM), nano insulation materials (NIM) and dynamic insulation materials (DIM) (Jelle et al. 2009, Baetens et al. 2010acde, Jelle et al. 2010a, Baetens et al. 2011, Jelle 2011b).

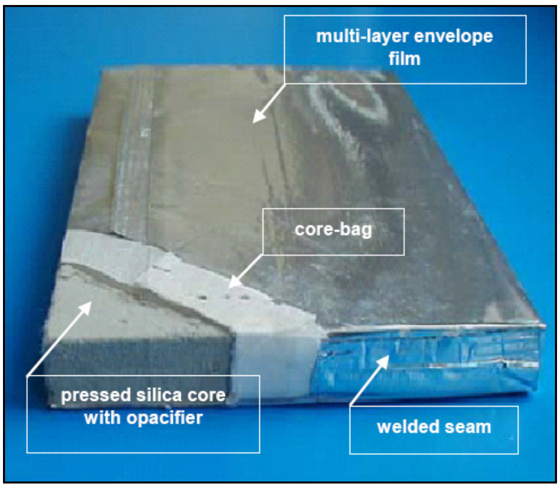


Figure 27. Vacuum insulation panel as a high performance thermal insulation material (Simmler et al. 2005).

Smart windows, e.g. electrochromic windows, represent yet another new building product which need to withstand the various climate strains, see Fig.28 (SAGE Electrochromics 2009). Electrochromic windows allow a dynamic control of daylight and solar energy in buildings (Jelle et al. 1992, Jelle and Hagen 1993, Lampert 1998, Jelle and Hagen 1999, Lampert 2004, Granqvist 2005, Jelle et al. 2007, Baetens et al. 2010b, Granqvist et al. 2010, Jelle and Gustavsen 2010, Jelle et al. 2012a), where commercial products are available (Baetens et al. 2010b). Important properties to be evaluated before, during and after accelerated climate ageing are visible solar transmittance modulation, solar transmittance modulation, solar reflectance modulation, colouration efficiency, cycling lifetime, switching time and memory effect among others.

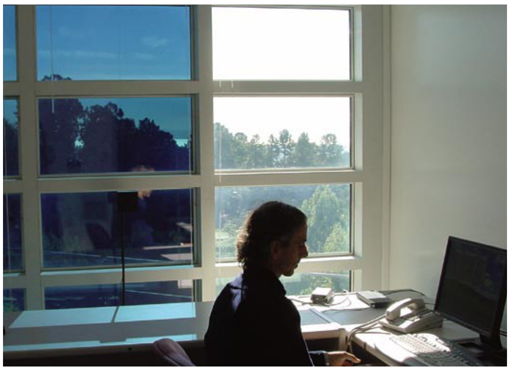


Figure 28. Example of a smart window for dynamic control of daylight and solar energy in buildings (SAGE Electrochromics 2009).

8.7. Ageing of Vacuum Insulation Panels

Accelerated ageing of vacuum insulation panels (VIP), both as stand-alone panels and inside a timber framework has been studied (Wegger et al. 2010, Wegger et al. 2011), where changes in thermal conductivity was one important property to determine. The experimental results were compared with theoretical models and predictions. Appurtenant theoretical, numerical and experimental investigations of these VIPs have been carried out by Grynning et al. (2009), Baetens et al. (2010ae), Haavi et al. (2010), Grynning et al. (2011) and Sveipe et al. (2011).

Figure 29 shows accelerated climate ageing tests of VIPs in a vertical climate simulator according to Nordtest Method NT Build 495 (2000), where one VIP was placed inside a timber framework and one VIP was directly exposed to the climate strains. The directly exposed VIP experienced delamination of the exterior fleece cover (for satisfying fire regulations), whereas the VIP inside the timber framework showed no sign of delamination. Heat ageing tests of VIPs were also performed, where the VIPs experienced a similar delamination of the exterior fleece cover, which is depicted in Fig.30. Measurements showed that this delamination had no effect on the thermal conductivity, hence it was assumed that the delamination was restricted to the outer fleece leaving the VIP air and moisture barrier intact. In order to accelerate the air and moisture diffusion into the VIP, an overpressure was applied, resulting into a visible compression of the VIPs as depicted in Fig.31 and increased thermal conductivity values of the VIPs. For a comprehensive summary and further details of these theoretical and experimental investigations of VIP ageing it is referred to the work by Wegger et al. (2011).

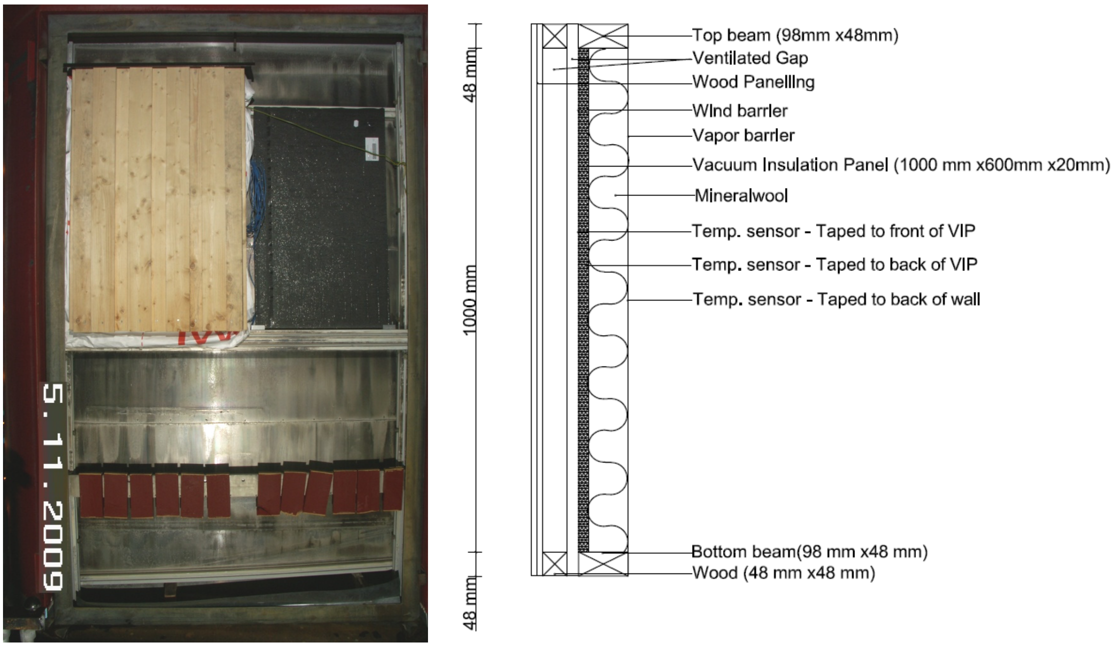


Figure 29. Accelerated climate ageing of VIPs inside a timber framework (top left in photo) and directly exposed (top right in photo) in a vertical climate simulator according to Nordtest Method NT Build 495 (2000). The drawing to the right depicts the timber framework with a VIP (Wegger et al. 2011).

Figure 30. Visible delamination of VIP fleece cover after heat ageing at 80°C for approx. 1 month. Similar delamination was observed for the directly exposed VIP in Fig.29, whereas the VIP inside the timber framework in Fig.29 did not experience any delamination (Wegger et al. 2011).

Figure 31. Visible compression of VIPs exposed to 14 bar overpressure. Pressurized VIP to the left, compared to a normal VIP to the right. The overpressure was applied in order to accelerate the air and moisture diffusion into the VIP (Wegger et al. 2011).

9. PROTECTION TOWARDS CLIMATE EXPOSURE

The protection of building materials, components and structures towards the climate exposure is not within the main scope of this work. Nevertheless, a few issues will be mentioned in the following. Various paths and strategies are followed in order to obtain a sufficient or satisfactory protection versus weather exposure and ageing. These strategies might be divided into the following groups:

- Avoid direct climate exposure.
- Allow healing of exposed parts.
- Climate adaption including climate changes.
- Increase at a material level the durability versus various exposures.
- Maintenance at specified intervals.
- Replacement at specified intervals.

An often used strategy is to avoid direct climate exposure. A well-known example is the application of large roof protrudings protecting large parts of the facades towards wind-driven rain and solar radiation exposure. Another example within this category is to protect less durable materials behind more durable materials, e.g. using glass structures as the outer weather skin protection. Naturally, paint application on top of substrate materials like wood, metal or concrete surfaces may also be viewed to belong within this category, with respect to the substrate materials. It should also be noted that during the building period, various materials, components and structures should be protected towards the weather exposure, otherwise several building damages may occur, e.g. material degradation by ultraviolet radiation and moisture problems related to trapped-in water. One solution is to apply a weather protection system (WPS) during the building period.

Another strategy is to allow healing of the exposed parts. One of these strategies involves the development of advanced materials technology with so-called self-healing materials, i.e. materials able to repair themselves, e.g. paints able to automatically fill and repair occurring scratches and cracks. Such self-repairing protection means are also being developed for the car and clothing industries. Note also that the instantaneous formation of an oxide layer on aluminium surfaces exposed to air may be put into this category. However, less advanced or less material-focused healing strategies do also exist. One of these involves to assume that some degradation agents will enter the building envelope, where the task will then be to ensure that these degradation agents are allowed to leave the exposed building parts before they do any irrecoverable damage. A typical example is to ensure that wind-driven rain entering into a window or building envelope will be drained or evaporated towards the exterior again. These strategies involves the application of the two-stage rain and air tightness principle and aerated or breathing water repellent materials, components and structures, e.g. aerated wooden cladding and vapour permeable (breathing) water repellent paints. The two-stage rain and air tightness principle is extensively used in windows, employing an outer rain screen (cladding), drainage grooves reducing the wind speed and draining any incoming water out again, and finally an airtight weather stripping which is not supposed to be let in contact with any water, as the water should be drained away before reaching the airtight weather stripping.

Climate adaption, i.e. to construct or adapt the building according to a specific or local climate, is a well-known protection strategy, although it is unfortunately not always satisfactorily followed. Note also that rather large local climate variations may occur, e.g. with respect to solar exposure, wind-driven rain, wind velocities and wind directions, due to topography, nearby buildings and various obstructions. It should also be noted that in addition to the climate exposure through the air on a building's walls and roof, the building is also subjected to various exposures from the ground, e.g. water, radon and earthquakes. Radon exposure in indoor air is highly dependent upon radon diffusion and air leakage into the building from the building ground (Jelle et al. 2011, Jelle 2012), and there may be large local variations of radon concentration in the building ground. Contrary to the climate adaption strategy is to construct all buildings with the same and at such a high level of durability versus climate exposure, that these buildings may be erected anywhere within a specified large or vast climate region. As there is in general a common consensus that the climate is changing towards a more severe climate, e.g. a warmer, wetter and wilder climate, throughout the world, it will be important to account for these changes towards a more extreme weather for both existing buildings and new ones to be built in the future. The studies by Kvande and Lisø (2009), Lisø (2006ab), Lisø and Kvande (2007), Lisø et al. (2006, 2007) and Nordvik and Lisø (2004) could be noted in this respect.

To increase at a material level the durability and robustness versus various exposures is one key protection strategy, which is being performed for both existing materials and during development of new materials. Depending on the actual application in the building envelope, the materials have to withstand various levels of the climate exposure factors given in section 3.1. Many polymer materials have been added photo-stabilizers or UV-stabilizers in order to increase the durability against solar radiation. Materials like e.g. paints are also designed with specific water repellent and vapour permeable (breathing) properties. Nanotechnology is increasingly being applied in many fields, also with respect to increase the durability and thereby prolong the service life of miscellaneous building materials, e.g. research conducted on nanoparticles in paints intended for wooden cladding (Fufa et al. 2011ab). As earlier noted a solar material protection factor (SMPF) and a solar skin protection factor (SSPF) have been introduced and defined by Jelle et al. (2007), which enables the measurement and calculation of the capability of glass and other transparent structures to protect materials and human skin from degradation caused by solar radiation. For studies some examples on photostabilization and modification of wood see e.g. the work by Evans (2009), Jebrane et al. (2009), Pandey et al. (2009), Prakash et al. (2006) and Prakash and Mahadevan (2008).

Maintenance at specified time intervals has been, is and will be a major protection strategy in the building and construction sector. Clever maintenance strategies able to determine the optimum maintenance will be cost-effective and reduce negative environmental impacts. Naturally, if the other protection strategies mentioned above are as good and effective as possible, the need for maintenance will be reduced to a minimum. Replacement at specified intervals might also be viewed as a protection strategy, i.e. with regard to the rest of the structure, although replacements may normally most often take place when it is required or desired due to extensive damages or a need to upgrade the building, e.g. retrofitting to obtain a larger thermal insulation resistance.

Finally, within the protection strategy philosophies, it is noted that carrying out accelerated climate ageing of building materials, components and structures in the laboratory, is an adequate and powerful tool for ensuring sufficient and satisfactory durability towards climate exposure.

10. CONCLUSIONS

The main climate exposures and how these may be reproduced and applied in laboratory in various ways have been examined. Thus, crucial properties of building materials, components and structures and their durability towards climate strains may be investigated within a relatively short time period compared with natural outdoor climate ageing. Examples of miscellaneous climate ageing laboratory apparatuses, ageing methods and building product properties to be tested before, during and after ageing are given. Furthermore, a calculation method for estimating acceleration factors is also demonstrated and discussed. Various ageing examples are shown and dixcussed. An extension is drawn towards the need for testing of new materials and solutions. It is concluded that accelerated climate ageing should be carried out in order to avoid building damages, either at a material, component or structural level. Accelerated climate ageing will pay off with respect to both time, costs and reputation, and will ensure that advances within materials science and engineering satisfy the various durability requirements.

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