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The influence of solar reflective black pigments on the durability of wood coatings

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This thesis was made in collaboration with Tikkurila Oyj. The purpose of this thesis was to study the influence of solar reflective black pigments on the durability of wood coatings. In addition, the aim was to examine the heat build-up effect on wood coatings when incorporating solar reflective pigments in exterior wood finishes. This thesis consists of two parts: a theoretical part and an experimental part.

The theoretical part of this thesis focuses on pigments, weathering stress factors, and accelerated weathering testing. Information was collected to create an overview on solar reflective pigments.

In the experimental part seven different solar reflective black pigments and two reference pigments were tested incorporating them to four different types of wood finishes. The effectiveness of solar reflective black pigments was tested in wood coatings using surface temperature measurements when the specimens were exposed to a halogen lamp. The influence of solar reflective black pigments on the durability of wood coatings was tested in accelerated weathering tests.

The test results showed that all the tested solar reflective black pigments were able to decrease the heat build-up approximately 10 °C compared to reference pigments. Although some of the pigments showed good results in both accelerated weathering test and surface temperature measurements, the results were slightly deviated between the different types of wood finishes. Further studies are needed to test the suitability of pigment for different types of wood finishes.

Information and test results found in this thesis provide a basis for the further studies and can be utilized in the company’s future development activities.

Keywords	Pigment, accelerated weathering testing

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Tämä insinöörityö tehtiin Tikkurila Oyj:lle. Työn tarkoituksena oli tutkia aurinkoa heijastavien mustien pigmenttien vaikutusta puunsuojatuotteiden kestävyyteen. Lisäksi tarkoituksena oli tutkia aurinkoa heijastavien mustien pigmenttien vaikutusta lämmönkertymiseen pinnoitteen pinnalla, kun niitä on lisätty puusuojatuotteisiin. Työ muodostuu kahdesta kokonaisuudesta: teoriaosasta ja kokeellisesta osasta.

Teoriaosassa keskityttiin pigmentteihin, säärasitustekijöihin ja nopeutettuun sääntestaukseen. Tietoa kerättiin aurinkoa heijastavista pigmenteistä yleiskuvan muodostamiseksi.

Kokeellisessa osassa testattiin seitsemää eri mustaa aurinkoa heijastavaa pigmenttiä sekä kaksi eri referenssi pigmenttiä sisällyttäen niitä neljään erilaiseen puusuojatuotteeseen. Aurinkoa heijastavien pigmenttien toimivuutta puupinnoilla testattiin tekemällä pintalämpötilamittauksia, kun kappaleet ovat altistettuna halogeenilampulle. Aurinkoa heijastavien mustien pigmenttien vaikutusta puupinnoitteiden kestävyyteen testattiin nopeutetulla sääntestauksella.

Testitulokset osoittivat, että kaikki testatut aurinkoa heijastavat mustat pigmentit pystyivät vähentämään lämmönkertymistä pinnoitteen pinnalla noin 10 °C:lla verrattuna referenssi pigmentteihin. Vaikka jotkut pigmenteistä osoittivat hyviä tuloksia sekä nopeutetussa sääntestauksessa että pintalämpömittauksissa, tulokset olivat hieman hajanaisia eri pinnoitteiden välillä. Lisätutkimuksia tarvitaan pigmenttien soveltuvuuden testaamiseksi tuotekohtaisesti.

Työstä löytyvät tiedot ja testitulokset toimivat pohjana lisätutkimuksille ja niitä voidaan hyödyntää yhtiön tulevaisuuden kehitystoiminnassa.

Avainsanat	Pigmentti, nopeutettu sääntestaus

Contents

Definitions

Appendices

Appendix 1. Selected volume concentrations
Appendix 2. Dry film thicknesses of wood finishes
Appendix 3. Evaluation of accelerated weathering tests
Appendix 4. Pictures of accelerated weathering tests (Coating A)
Appendix 5. Pictures of accelerated weathering tests (Coating B)
Appendix 6. Pictures of accelerated weathering tests (Coating C)
Appendix 7. Pictures of accelerated weathering tests (Coating D)
Appendix 8. Color measurement results
Appendix 9. Color measurement graphs

Definitions

UV	Ultraviolet radiation. Electromagnetic radiation with a wavelength of 300-400 nm.
VIS	Visible light. Electromagnetic radiation with a wavelength of 400 – 700 nm.
IR	Infrared radiation. Electromagnetic radiation with a wavelength of 700 – 2500 nm.
TSR	Total Solar Reflectance is the measure of the amount of sunlight reflected from an object.
Color Index	Colorants are listed according to Color Index Generic Names and Color Index Constitution numbers.
CIElab	The most complete color space (L*, a*, b*) specified by the International Commission on Illumination.

1 Introduction

This thesis was made in collaboration with Tikkurila Oyj. The subject of this thesis is part of a wider innovation research. New IR-reflective and IR-transparent pigments have been introduced to the market and the objective of this thesis was to evaluate the effect of new functional pigments on the durability and functionality of wood coatings.

The purpose of this thesis was to study how solar reflective black pigments affect coating degradation on wooden substrates, by using accelerated weathering tests. In addition, the aim was to examine the heat build-up effect on wood coatings, when incorporating solar reflective pigments in exterior wood finishes.

The effects of solar reflective pigments on metallic surfaces have been studied extensively in recent years, but less attention has been paid to the functionality of solar reflective pigments on wooden substrates. Information was collected to create an overview on solar reflective pigments, and experiments were carried out to test the efficiency of solar reflective pigments on wood coatings in practice.

It is known that objects painted with light colors tend to reflect heat, and stay relatively cool to touch when exposed to the sun. Conversely, dark surfaces tend to absorb heat with a subsequent temperature increase. In addition, substantial variations of temperature expose pigmented wooden substrates to a massive stress. High temperatures and UV radiation cause premature ageing of the surface and shorten the lifetime of the coating. The main purpose of solar reflective pigments is to keep the coated item cooler and improve the durability of the coating.

This thesis consists of two parts: a theoretical part and an experimental part. The theoretical part of this thesis focuses on pigments, weathering stress factors, and accelerated weathering testing. The experimental part examines only black pigments and four different types of wood finishes. Since the time for the experimental part was limited, it was not possible to repeat all of the tests for demonstrating the statistical reliability of the experiment.

Theoretical part

2 Pigments

2.1 Pigments and colorants in general

Coloring agent is the generic term for all color-imparting substances. They can be divided into dyes and pigments, according to their solubility in the surrounding medium. In contrast to pigments, dyes are soluble in the surrounding medium, while pigments are insoluble in the medium in which they are applied. [1, p.15; 2, p.11]

(1) Pigment is a substance consisting of finely divided particles which are insoluble in the surrounding in which they have been applied. Pigments are used as coloring agents or by virtue of their corrosion-inhibiting or magnetic properties. [2, p.111]

(2) Pigment dispersions are pigment concentrates in which the pigments are dispersed thoroughly into the carrier material. [5]

(3) Colorants are pigment concentrates, which consist of pigments, additives, solvents and sometimes binders. Colorants are strictly controlled in color, color strength and rheology. [4, p.31]

(4) Easily dispersible pigments are produced by admixing a water slurry of a pigment with an oil in water type emulsion which contains a varnish. They can be easily incorporated into the paint systems with a dissolver and without an additional milling step. [6]

There is a classification system for colorants known as Color Index (C.I). Colorants are listed according to Color Index Generic Names and Color Index Constitution numbers. [1, p.15]

In this thesis, the term "colorant" is generally used when referring to pigments, colorants or easily dispersible pigments. The colorants discussed in this thesis are also characterized by their Color Index name (C.I).

2.2 Inorganic and organic pigments

Pigments can be divided into organic and inorganic, on the basis of their chemical composition. Table 1 demonstrates the differences between these two pigment families. [3, p.2]

Organic pigments are used mainly for high tinting strength and brilliant shades of color, while inorganic pigments are useful when high quality opacity is needed. [7]

Most inorganic pigments have extreme fastness to light and weathering and excellent hiding power. However, some inorganic pigments have coloristic limitations and application problems. Organic pigments are generally more intensely colored and more brilliant compared to inorganic pigments. Many organic pigments, however, have limited lightfastness and weather resistance. [1, p.20; 2, p.140]

Table 1. Comparison of organic and inorganic pigments [1, p.20; 8, p.140]

Pigment properties	**Inorganic**	**Organic**
Color	Dull	Bright
Hiding power	Excellent	More or less transparent
Color strength	Middle to low	Normally high
Chemical resistance	Very good/ Varies (depending on compound)	High
Particle size	Large (0.1-0.4 µm)	Small (<0.1 µm)
Light and weathering fastness	Excellent	Insufficient
Heat resistance	Generally higher	Generally lower
Scattering power	Usually higher	Usually lower

2.3 Important features of pigments

Application-oriented properties, such as the rheological behavior of the pigmented coating, hue, scattering ability of the pigment, color intensity, and different types of fastness properties, are dependent on the size and distribution of pigment particles. In addition chemical structure, surface properties and crystallinity have an effect on pigment performance and properties. [2, p.114; 7]

2.3.1 Physical properties

Pigments can occur as single or primary particles, aggregates, or agglomerates. (Figure 1.) Primary particles are single crystals with lattice disorders, or combination of several lattice structures. Figure 2 indicates that there are different shapes of primary particles; cubes, platelets, needles, bars and irregular shapes. The size and shape of the pigment particles affects the dispersion properties and quality of the pigments. [2, p.112-113; 9, p.12]

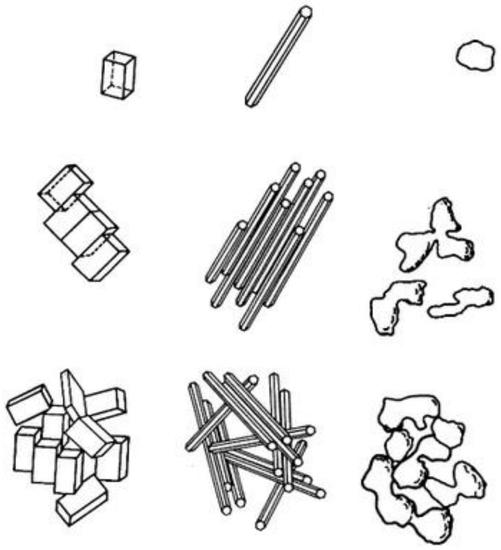


Figure 1. Primary particles, aggregates and agglomerates [3, p.27]

Aggregates are primary particles which have grown together and are aligned side by side. Their total surface area is smaller than the sum of the surface areas of the primary particles. Aggregates cannot be separated by a dispersion process. [2, p.112-113]

Agglomerates are groups of primary particles or aggregates which are aligned at their corners and edges but not grown together. Agglomerates can be separated by a dispersion process. [2, p.112-113]

Flocculates are assemblies of wetted primary particles, aggregates or smaller agglomerates which can usually be broken up by low shear forces. [3, p.25-27]

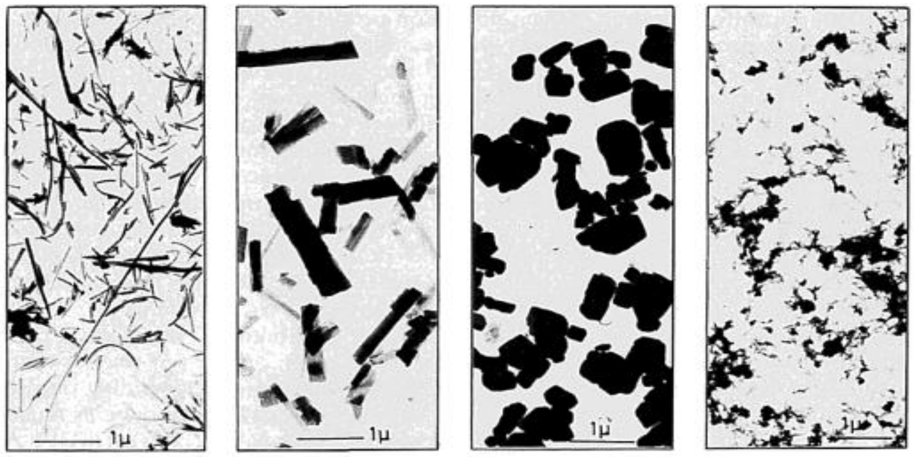


Figure 2. Examples of different crystal forms of pigment particles [3, p.26]

2.3.2 Optical properties

Pigments have a significant influence on the optical properties of paints. Optical properties of pigments are due to a combination of two effects which result from the interaction of the pigment particles with visible light: light absorption and light scattering. [8, p.124]

Scattering means the ability of pigment particles to turn the travel direction of light, whereas absorption means the ability of pigment particles to change the energy of light into thermal energy. Scattering depends on the refractive index of material, particle size, and dispersion. Absorption is influenced by the structure of the pigment particles and the chemical composition of the pigment. Figure 3 demonstrates the effect of pigment particles on the optical properties of the pigment. [10, p.43]

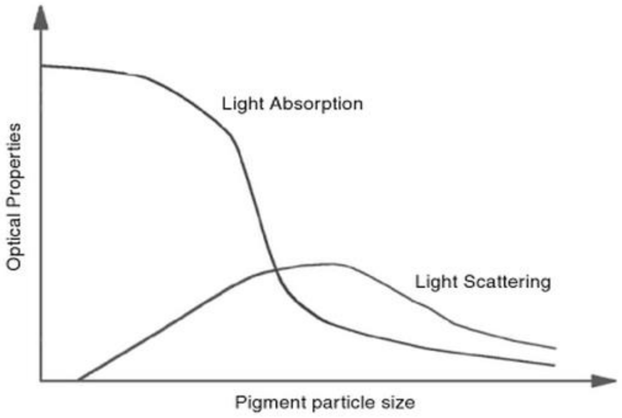


Figure 3. Effects of pigment particle size on the optical properties [11, p.129]

2.3.3 Color and light

Three factors are needed for the perception of color; 1) a source of light, 2) an object, which absorbs all the colored light rays, except those corresponding to the color of the object, and 3) the eye of the observer, which receives the reflected colored light and sends the message to the brain. [4, p.4]

Visible light is electromagnetic radiation with wavelengths of 400-700 nm (Figure 4.) Black absorbs all the light rays, whereas white reflects all light rays. [3, p.48; 2, p.124]

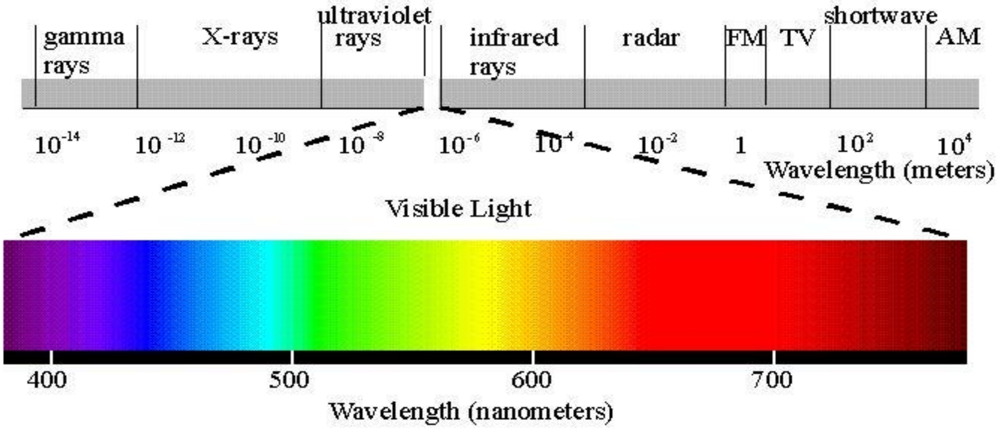


Figure 4. Electromagnetic spectrum and the visible light areas [4, p.6]

Brock, Groteklaes and Mischke in their book *European Coating Handbook* have stated that:

> “The color-imparting properties of pigment, such as color intensity, hiding power and transparency, as well as their influence on gloss, are dependent not only on their chemical composition but also on physical properties such as crystalline structure and the shape and size of the crystals.” [2, p.112]

Hiding power is the ability of a pigmented medium to cover the color of the substrate. The hiding properties of a paint film are influenced by the absorption and scattering of incoming light on the pigment surface. In addition, the thickness of a film and the magnitude of the color differences of the substrate have an effect on the hiding power. [2, p.125, 142; 3, p.55]

2.3.4 Fastness properties

Fastness is one of the most important properties of pigments. Pigments are expected to withstand the effects, without discoloration, when exposed to external factors, such as exposure to weather, light, heat, solvents and other chemicals. [8, p.12]

The size of the pigment particles has an impact on weathering fastness. Pigments containing bigger particles are more resistant to weathering compared to pigments with small particles. Radiation which cleaves the pigment structure, penetrates only 0.03 – 0.07 µm deep into the pigment surface and, as a consequence, larger particles which are centrally located in such large units, resist light and protect the surface from rapid hatching. [10, p.136; 3, p.130]

3 Solar reflective pigments

3.1 Solar reflectance

As Figure 5 demonstrates, the solar spectrum consists of 3 % of ultraviolet light (300-400 nm), 39 % of visible light (400-700 nm) and 58 % of near-infrared light (700-2500 nm). [12]

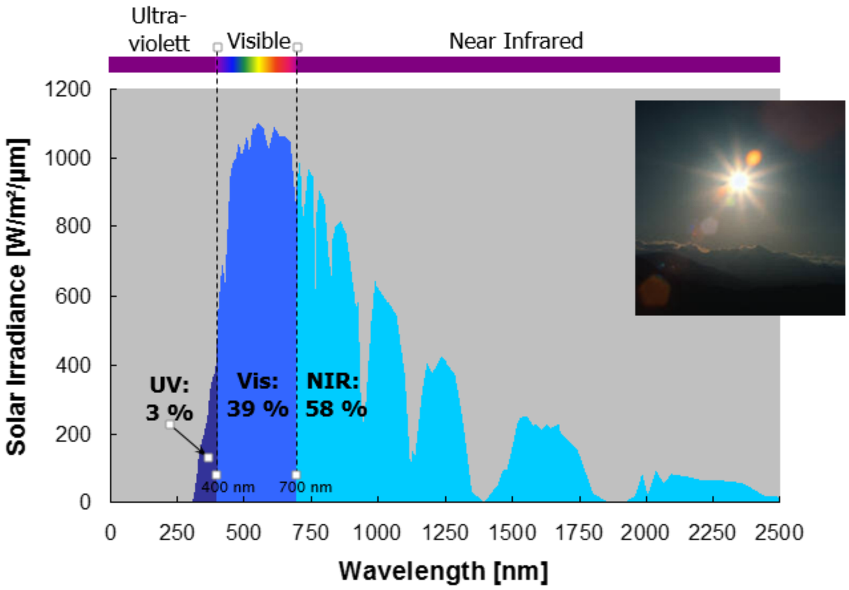


Figure 5. Solar spectrum [12]

Pigments interact with solar radiation by absorption, reflection and scattering. The visible part of the electromagnetic spectrum is obvious in the form of our color impression. Pigments can additionally interact with UV radiation and near infrared radiation. Although it is known that UV radiation causes pigment fading, IR radiation dominates the overall irradiated solar energy by more than 50 %. Radiation in the infrared region is invisible to the naked eye, but we can still feel the effects of its energy in the form of heat. [13; 14; 15]

3.2 Definition of IR-reflective and IR-transparent pigments

The primary purpose of IR-reflective pigments and IR-transparent pigments is to keep objects cooler than they would be by using standard black pigments. In addition, pigment interaction with wavelengths outside the visible part of wavelengths can have interesting effects on coating properties such as usability and durability. [13; 16]

Infrared transparent pigments are substantially transparent in the near-infrared wavelength region. They neither absorb nor reflect in the IR region of the spectrum. Infrared reflective pigments refer to a pigment with reflectance of near-infrared radiation. IR-reflective pigments are also non-absorbing in the IR region. [17; 18]

The general benefits of IR-reflective pigments are: longer potential life-cycle due to less polymer degradation and thermal expansion due to lower temperature, aesthetically pleasing color and improved system durability and less thermal degradation. [16]

3.3 Solar heat management

The amount of total energy absorbed and emitted by a topcoat determines the heat build-up of the coated surface and results in a final surface temperature. The pigmentation of the coating material has the main influence on heat-build up performance. For cooling effect, the key is to reflect infrared and absorb and reflect in the visible region to produce the needed color. [13; 16]

The purpose of using solar reflective coatings is to reflect a significant amount of solar radiation from colored surfaces to keep them cooler. [14] Reflectivity is achieved by the physical back-scattering of solar radiation by pigment particles. This is well-known for the visible range. [19]

To achieve cool surfaces, the pigments in the coating need to reflect as much energy as possible. This reflection ability can be expressed as the Total Solar Reflectance (TSR) value (100 % is total reflection and 0 % is total absorption). Therefore, pigments with high TSR values show a high reflection combined with low heat build-up, and vice versa. Usually, white coatings exhibit a total solar reflectance of 75 % or more. A white coating with total solar reflectance of 75 % by definition, absorbs 25 % of the incident energy. A black coating, based on carbon black pigmentation, may have a TSR as low as 4 %, therefore absorbing 96 % of the incident solar energy. [14; 19]

Cooler surfaces are beneficial to materials and users in many ways. Thermal stress in materials is reduced, thus contributing to a better durability of temperature sensitive materials. [14] Wood is known to be more of an insulating material than other building materials, such as steel. For this reason, one might assume that the accumulation of heat in wood would be relatively low. However, heat accumulation in wood exposed to high temperatures may cause problems. Heat accumulation causes drying of the wood surface which may lead to chalking. Resin exudation occurring with coniferous species, widely used in outdoor uses, usually leads to critical failure of the finishing system, followed by wood moisture and fungus problems. [20]

4 Black pigments used in this work

The most important black pigments are

- carbon blacks (PBk7)
- iron oxide blacks
- various mixed phase oxide pigments such as spinel black [2, p.129]

4.1 IR-reflective and IR-transparent black pigments

Standard black pigments, for example carbon black and iron oxide black, have low infrared reflectivity whereas the white pigments (TiO_2) have the highest reflection ability. [13]

Attempts have been made by pigment manufacturers to replace standard black pigments which are reflective in the IR region. Clearly such reflective pigments are also substantially non-absorbing in the IR region. In addition to the non-absorbing and reflective pigments are black pigments which are transparent to IR wavelengths. In other words, they neither absorb nor reflect the IR region of the spectrum. [18]

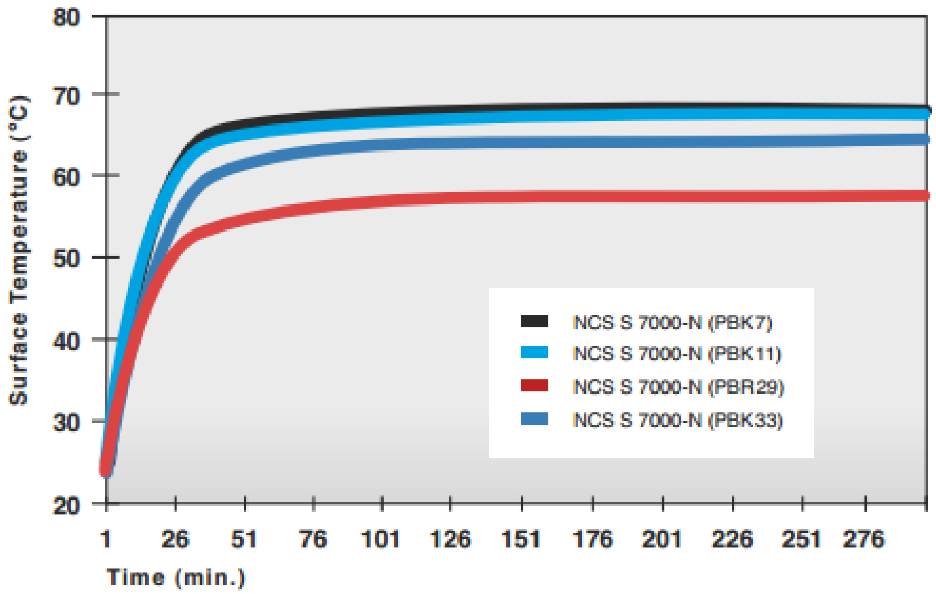


Figure 6. Heat build-up profiles using different black pigments [14]

Ravenswaaij and Huijnen in their article “Solar reflective colorant for building exteriors and facades” demonstrate the experiments which were done by testing solar reflective coatings. Figure 6 shows the effect of replacing the standard black pigments (PBk7 and PBk11) with PBr29 and PBk33 pigments. The test results confirms that replacing the standard black pigments with IR-reflective black pigments causes less heat build-up on the surface. [14]

4.2 Inorganic pigments

4.2.1 PBk7

Carbon black

Carbon black is the most commonly used black pigment due to its excellent properties. The structure of carbon black is partially microcrystalline carbon, whose almost spherical primary particles have grown into larger particles which form chains and clusters. Carbon black is finely divided and it has a very small particle size, from 10 to 50 nm. [2, p.130-132]

Carbon black is fast to light and it has good chemical resistance, for example it is resistant to acid, alkali and solvents. Carbon black has an intense black color, meaning, it has excellent light and weathering stability and outstanding depth and intensity of color. Carbon black pigments are the hardest pigments to disperse because of the high strength they have. [8, p.134; 10, p.135]

4.2.2 PBk11

Iron oxide black Fe_3O_4 (magnetite)

Iron oxide black (PBk11) is one of the synthetic iron oxide pigments. It contain 69 % of Fe_2O_3 and 31 % FeO. The structure of black iron oxide is spinel, mainly cube shaped and the particle size of iron oxide black pigment is 0.1 – 0.6 µm. [1, p.43-47]

Black iron oxides, in general, have excellent color intensity, good hiding power and they are fast to light and resistant to weathering. Nonetheless, iron oxide pigments used in paint films tend to undergo surface degradation when exposed to the weathering elements, leading to reduced gloss, chalking, and a slight change in color. The depth and color intensity of iron oxide black is lower than carbon black, but it disperses more easily. [2, p.134-136; 8, p.134]

4.2.3 PG17

Chromium oxide green Cr_2O_3

Chromium oxide green (PG17) contains pure chromium (III) oxide. It has a corundum crystal structure, the particles are usually spheroidal and an average particle size is 0.3 – 0.4 µm. [1, p.73-77]

Due to the chemical structure of chromium oxide green, it is very heat resistant and hard. Chromium oxide green pigments are fast to light and weathering, and have excellent hiding power, due to high light-scattering and absorption. It has poor opacity and staining power, but it has an extreme resistance to heat, light and chemicals. Chromium oxide green pigments has high reflectance in infrared light. [8, p.134; 10, p.94]

4.2.4 PBr29

Chromium iron brown $(Fe,Cr)_2O_3$

Chromium iron brown is categorized to complex inorganic colored pigments, more specifically to spinel pigments. The structure of chromium iron brown is spinel with lattice defects. [1, p.96]

Complex inorganic pigments have excellent fastness properties. They are resistant to light, weathering and chemicals. [2, p.137]

4.3 Organic pigments

4.3.1 PBk32

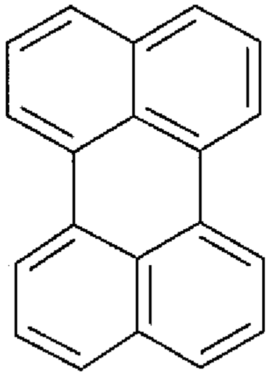


Figure 7. General structure of perylene pigment [21]

Perylene black pigments are intense black pigments with very dark olive or violet undertones. The color strength of these pigments is excellent.

Perylene blacks (PBk32) have excellent light fastness and weather resistance, but some of them have a tendency to darken upon weathering. Some of the perylene pigments are also resistant to certain chemicals. Due to various hues of perylene black, they satisfy certain spectral requirements in the IR region. Perylene blacks absorb visible radiation but they are transparent to near infrared radiation. [3, p.9, 476, 482; 17]

5 Ageing of coated wood by weathering

5.1 Factors affecting the weathering of wood coatings

The primary reason for ageing of coatings in outdoor use is weathering stress. Weathering stress factors which cause coating ageing are solar radiation (ultraviolet, visible, and infrared light), temperature, moisture, biological factors, oxygen (O_2) and air pollutants (Figure 8). These elements may affect individually, and also in combination, to cause coating failure. [22, p.12, 22; 23, p.643]

Weathering stresses cause loss of gloss, yellowing, bleaching, haze increase, formation of cracks, chalking, fading and color change of a coating. [23, p.643]

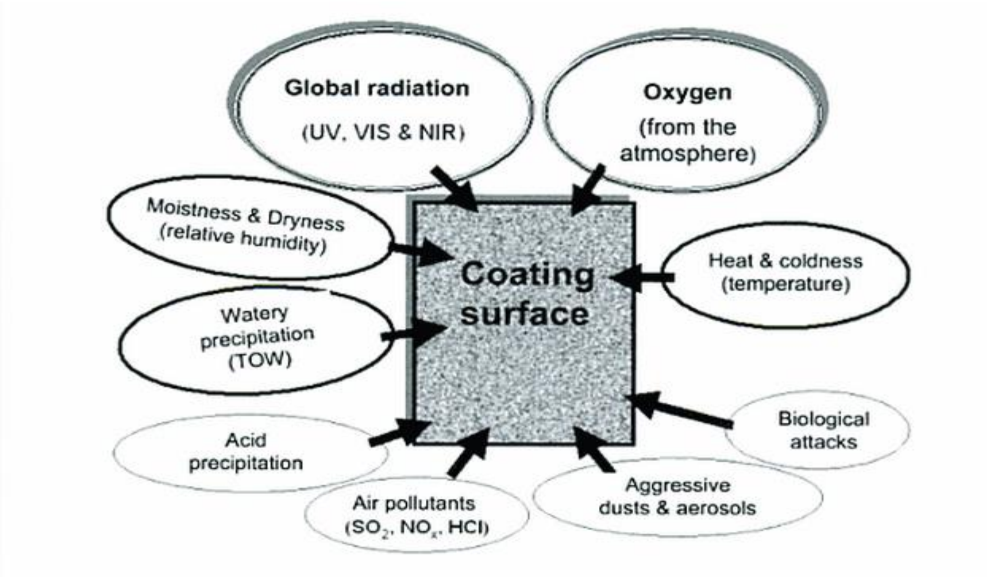


Figure 8. Weathering factors influencing a coating surface [22, p.12]

5.1.1 Solar radiation

The solar electromagnetic spectrum that reaches the Earth's surface consists of 5 % of ultraviolet radiation (300-400 nm), 42 % of visible light (400- 700 nm) and 53 % of near infrared radiation (IR) (700-2500 nm). UV radiation can be divided into UVA (320-400 nm) and UVB (<320 nm). Each spectral region has its own effect on the material. [24, p.317, 349] Different sources give slightly different values for the solar electromagnetic spectrum, but the values are very close, as can be seen in chapter 3.1.

Solar radiation, more specifically UV light, is the main weathering stress factor responsible for the most of the damages of a coating. Solar radiation gradually changes the chemical structure of a coating and, as a consequence, leads to discoloration, loss of gloss, embrittlement and chalking of the coated wood. [23, p.621, 643; 25, p.71]

UV light is the most dangerous part of radiation for polymers. UV radiation has higher energy photons compared to visible radiation. These photons are capable of cleaving the polymer bonds. Generally, the shorter the wavelength of incoming radiation, the higher its energy, and the more damaging its effect is on polymers. For example UV radiation, especially UVB (<320 nm), is the most energetic and it is capable of cleaving the polymer bonds. It is responsible for most of the photochemical degradation of the coating. [22, p.36-37; 23, p.621]

The visible part of the solar electromagnetic spectrum is responsible for a limited amount of physical degradation. It can cause discoloration without changing the physical properties of material. The infrared region causes heat build-up to occur on radiated specimens. Absorption of infrared region wavelengths causes specimen temperatures to rise, which in turn leads to an increase in the rate of photochemical degradation of the coating. [23, p.622]

5.1.2 Water and moisture

Wood used outdoors is exposed to water in different forms; such as rain, snow, dew, hail and vapor. Moisture, in combination with solar radiation, has a significant impact to the weathering of coatings. It causes blistering, flaking, mildew, and early loss of adhesion to wood coatings. [23, p.643; 22, p.49]

Water can affect material in two different ways; absorption and desorption. When water is absorbed in to the material, direct moisture can cause changes to the physical properties of the material. As the surface layers absorb moisture, a volume expansion is produced that places stress on the dry subsurface layers. Another way how water affects the material is desorption. It occurs during dry periods when the surface layers will lead to a volume contraction and, as a consequence, will lead to surface stress cracking. In addition, fluctuation between wet and dry periods may result in stress fractures. [26, p.16]

5.1.3 Temperature

Temperature is not as critical a weathering stress factor as UV radiation and water, but as the temperature increases, the rate of photochemical and oxidative reactions increase. In addition, the changes in temperature can cause cracking, peeling and checking of the coating. [23, p.643; 27, p.196]

The temperature on the surface has a direct effect on the rate of coating ageing. It is determined by irradiance, ambient temperature and wind velocity. The surface temperature is also determined by the absorbance and reflectance of the coating, which are typical coating properties. The higher the absorbed amount of radiation, the higher is the surface temperature. Generally dark-colored samples reach higher temperatures than light-colored samples. [22, p.45, 53]

Solar absorption in both visible and infrared regions is closely related to color, varying from about 20 % for white surfaces, to over 90 % for black surfaces; thus, materials of different colors will reach different temperatures on exposure. This surface temperature dependency on colors can have secondary effects on materials as well. For example, as a result of different surface temperatures, mildew and other biological growth will form and accumulate at different rates on materials of different colors. [26, p.15]

5.1.4 Oxygen

Photo-oxidation reactions, initiated by solar radiation in combination with oxygen, accounts for most polymer failures that occur during outdoor exposure. [28, p.1364] Absorption of radiation is the primary photophysical reaction of the ageing process. When light is absorbed by a polymer, it leads to a formation of free radicals causing photo-oxidation. Solar radiation in combination with oxygen causes the photo-oxidation which eventually leads to the polymer failures. [22, p.23]

5.1.5 Air pollutants

Air pollutants have less influence on coating ageing than the common variations of radiation, temperature, and moisture, during outdoor weathering. However, the action of certain air pollutants, such as acid rain, acid dew, and acid fog cause considerable coating damages. [22, p.59-61]

Acid rain reactions lead to discoloration and loss of surface integrity. Acid rain and absorption of UV light combined can cause chemical changes on wood surfaces, and deterioration of tensile strength. [29, p.528]

5.2 Degradation of paint film by weathering

Degradation of paint film by weathering, as shown in chapter 5.1, is caused by UV radiation, temperature, moisture, oxygen and air pollutants. Figure 9 shows the phenomenon of coating ageing that may be caused by these weathering stresses.

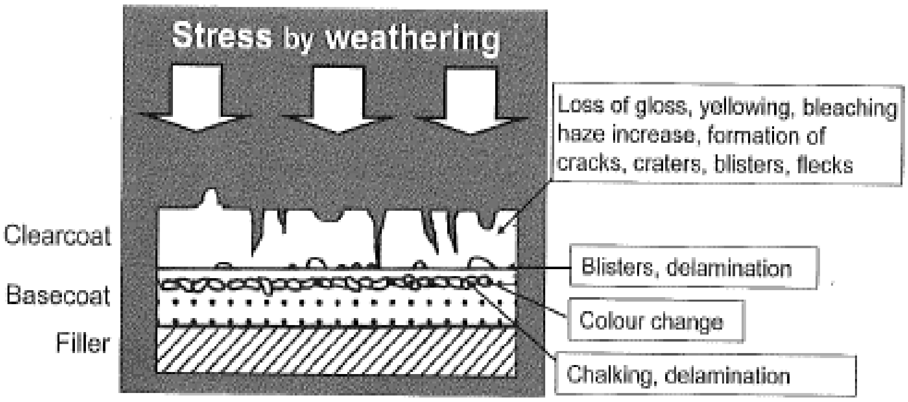


Figure 9. Degradation of coating [22, p.165]

In addition to these weathering stresses, wood finishes may fail also due to inadequate preparation or insufficient film thickness. [30]

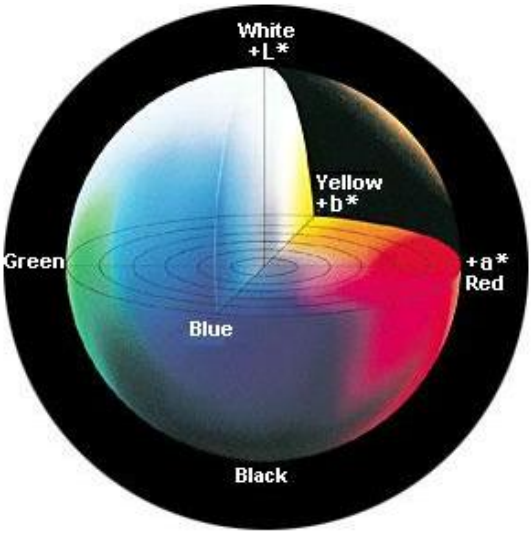
5.2.1 Color change

Color change is one of the most common ageing criteria in coating testing. Color change of coatings is due to different coating components or different coating layers. [22, p.171]

Color fading is the gradual change of color intensity. It is caused by photodegradation of colored pigments. Sometimes chalking can also cover the color, giving the impression of fading. [31, p.29]

Color differences can be detected visually when the objects are placed side by side. Even if the human eye is very accurate in defecting color differences, however, the measurement of color hues and numerical values are important. Colorimetry is developed for this purpose and can also be used to measure very small color differences. [32, p.57]

The color of the paint film can be measured by colorimetry, for example according to CIElab color space. The color space consists of two chromaticity coordinates, a* (green-red) and b* (blue-yellow), which define the hue of the color. These two coordinates are arranged at right-angles to each other on a fictitious horizontal color plane. A third coordinate, L*, defines the lightness value. L* is arranged at right-angles to the plane formed by a* and b* and characterizes greying as well as lightening of the coating surface. L = 0 is black and absorbs all the light, whereas L = 100 is white and reflects all the light. In addition, L = 50 is grey. [22, p.171; 32, p.53] Figure 10 illustrates the concept of CIElab color space.



+a = red
-a = green
+b = yellow
-b = blue

Figure 10. CIElab color space [33]

5.2.2 Chalking

The reason for chalking of paint films is that the non-bound powdery pigment particles on the surface of the paint film are released during weathering. This causes the formation of white chalky powder on the surface of the paint film. [34, p.117]

Chalking is due to the weathering factors of UV radiation combined with moisture and oxygen. Wood swells with moisture, and UV radiation penetrates to a certain extent into swollen wood. Radiation in combination with oxygen and water causes deterioration of the macromolecules. The binder slowly degrades and releases its hold on the pigments. With decreasing binder content the film will shrink. [34, p.118; 32, p.53]

5.2.3 Cracking and flaking

One of the possible damages in a paint film is cracking. Cracking of paint can occur for a variety of reasons. Often the cracking is due to tension of the paint film. Moisture changes in the wood will cause dimensional changes of the wood. Wood swells when it gets wet and shrinks when it dries. This will form a tension on the film and will lead to cracking of the paint film. Surface cracks can also be caused by paint ageing in the form of loss of elasticity. Too thick or hard surfaces of the paint layer can also cause cracking. Eventually the paint film, or part of it, peels off from the substrate and the paint film loses its protective ability. [35]

6 Protection of wood against weathering

Wood exposed outdoors undergoes a number of physical and chemical phenomena mostly caused by weathering stress factors, such as solar radiation, moisture and temperature. Weathering can be injurious to the surface and appearance of wood. Wood surfaces exposed to the weather without any finish are roughened by photodegradation and surface checking, change color, and slowly erode. [36, p.66-1]

The primary function of a wood finish is to protect the wood surface from the natural weathering process and help maintain appearance. The protection that surface treatment provides against light and water will be affected by the weather resistance of the bonding agents of the finish (drying oil, synthetic resins, latexes, etc.). [37]

There are two basic types of wood finishes; film-forming finishes and penetrating finishes. Film-forming finishes form a film on the wood surface and penetrating finishes penetrate into the wood surface leaving no distinct coating. Film-forming finishes include paints of all descriptions, varnishes, varnish stains, and solid-color stains. Penetrating finishes include oils, water repellents, solvent-borne stains, and preservatives. [37; 36, p.66-8] In this thesis, only wood finishes which were used in the experimental part, are presented below.

6.1 Wood oil

Wood oil penetrates into the wood and does not form a continuous film. It can penetrate into the wood in two different ways: flow as liquid into cut cells on the surface and absorption into cell walls. Wood oil protects the wood from weathering by slowing down the effects of humidity, UV light, rot-, mold- and blue stain fungus. [37, p.88; 30]

6.2 Non-film-forming wood stain

Non-film-forming wood stains, also called semitransparent penetrating stains are only moderately pigmented and thus do not totally hide the wood grain. The main use of wood stains is to enhance the characteristic appearance of wood. They protect the wood against humidity, UV light and fungi, and decrease the cracking and rapid ageing of wood. [11, p.40; 37, p.100; 36, p.66-9]

Since wood stains penetrate into the wood without forming a discrete, continuous layer, they will not blister or peel, even if excessive moisture enters the wood. The durability of any stain system is a function of pigment content, resin content, preservative, water repellent, and quantity of material applied to the wood surface. [27]

6.3 Film-forming wood stain

Film-forming wood stains form a film on the wood surface. It is usually made with much higher concentration of pigments than the semitransparent penetrating stains. A film forming wood stain usually hides the natural color and grain of wood. It protects the wood from weathering stresses. [37, p.89; 36, p.66-9]

6.4 Opaque paint

Opaque paint is defined in the standard SFS-EN 927-1:

> “A pigmented coating material, in liquid or in paste or powder form, which when applied to a substrate, forms an opaque film having protective, decorative or specific technical properties.” [38]

When paints are applied to a wood surface they do not penetrate it deeply. They cover the wood grain completely, forming an opaque film. Paints provide the best protection against UV radiation because they block the damaging ultraviolet light rays from the sun. [36, p.66-9]

Paints protect wood surfaces from weathering, hide some surface defects, provide a cleanable surface, offer many colors, and give certain gloss properties. Paints slow down penetration of moisture, decrease discoloration of wood extractives, and retard checking and warping of the wood. [30]

7 Testing by accelerated weathering

7.1 Accelerated weathering testing in a laboratory

Accelerated weathering chambers use a wide variety of light sources to simulate sunlight and the damage that it causes. [39, p.12-1] Accelerated weathering testing is developed for more rapid evaluation of the resistance of coatings to weathering than can be obtained by outdoor exposure tests. Several artificial light sources are used to accelerate the degradation of coatings. These light sources are filtered long arc xenon, fluorescent, metal halide lamps and carbon arc. [26, p.41] This thesis, however, focuses only on the xenon arc, more specifically Xenon Ci4000 Weather-Ometer, which was used in the experimental part.

In laboratory conditions, an accelerated testing equipment is used to simulate the degradation that occurs during actual outdoor exposure. Accelerated testing degrades coatings and coated specimens faster than exterior testing. In addition, a great advantage of accelerated weathering is that laboratory conditions are controllable and reproducible. [23, p.643]

According to the Atlas weathering testing guide:

> “Accelerated tests can run continuously at naturally occurring or higher irradiance than solar radiation, uninterrupted by the natural day/night cycle, seasonal variations, and weather conditions. Temperatures, thermal cycles, humidity, and water exposure also can be manipulated to maximum, but not unrealistic, stress levels.” [26, p.42]

7.2 Xenon arc lamp

7.2.1 Xenon instrument in general

An equipment with xenon arc was the first weathering machine developed in 1954. Nowadays the xenon arc is one of the most common light sources used in accelerated weathering testing. [22, p.115; 41] Xenon arc devices are used to expose specimens to filtered xenon arc light under controlled conditions including temperature, humidity and wetting. Various types of xenon arc light sources and various filter combinations are used to meet different conditions. [40]

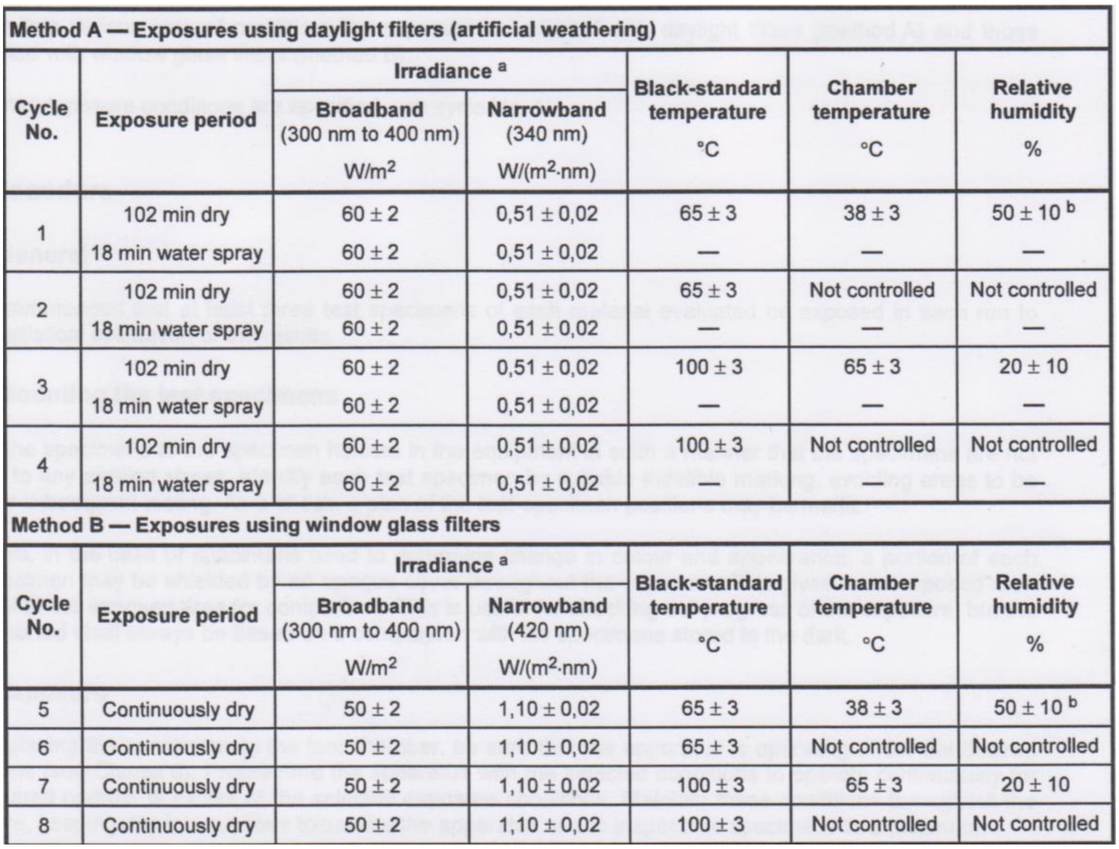
The xenon device attempts to reproduce the entire spectrum of sunlight, including ultraviolet (UV), visible light and infrared light. [41] In order to avoid overly high thermal stress of the test panels, the lamps, the optical filters, and other irradiated parts of the weathering device, appropriate filtering and cooling means are indispensable. [22, p.117]

Two different cooling systems are used; a water-cooled xenon arc and an air-cooled xenon arc. The type of cooling is reported not to have a major influence on spectral distribution, including the cut-on of the UV and, therefore, on the weathering results. [26, p.39; 22, p.117-118]

The xenon arc uses a system of intermittent water spray to simulate the effects of rain and dew. The water-spray cycle is especially useful for introducing thermal shock and mechanical erosion. [39, p.12-6]

Standard ISO 4892-2 determines the exposure conditions to be varied by selection of:

- the light filter(s)
- the irradiance level
- the temperature during exposure to light
- the relative humidity in the chamber during light and dark exposures, when exposure requiring control of humidity are used
- the way the test specimens are wetted
- the water temperature and wetting cycle
- the relative lengths of light and dark periods [40]



Method A — Exposures using daylight filters (artificial weathering)

Cycle No.	Exposure period	Irradiance a		Black-standard temperature °C	Chamber temperature °C	Relative humidity %
		Broadband (300 nm to 400 nm) W/m²	Narrowband (340 nm) W/(m²·nm)			
1	102 min dry	60 ± 2	0,51 ± 0,02	65 ± 3	38 ± 3	50 ± 10 b
	18 min water spray	60 ± 2	0,51 ± 0,02	—	—	—
2	102 min dry	60 ± 2	0,51 ± 0,02	65 ± 3	Not controlled	Not controlled
	18 min water spray	60 ± 2	0,51 ± 0,02	—	—	—
3	102 min dry	60 ± 2	0,51 ± 0,02	100 ± 3	65 ± 3	20 ± 10
	18 min water spray	60 ± 2	0,51 ± 0,02	—	—	—
4	102 min dry	60 ± 2	0,51 ± 0,02	100 ± 3	Not controlled	Not controlled
	18 min water spray	60 ± 2	0,51 ± 0,02	—	—	—

Method B — Exposures using window glass filters

Cycle No.	Exposure period	Irradiance a		Black-standard temperature °C	Chamber temperature °C	Relative humidity %
		Broadband (300 nm to 400 nm) W/m²	Narrowband (420 nm) W/(m²·nm)			
5	Continuously dry	50 ± 2	1,10 ± 0,02	65 ± 3	38 ± 3	50 ± 10 b
6	Continuously dry	50 ± 2	1,10 ± 0,02	65 ± 3	Not controlled	Not controlled
7	Continuously dry	50 ± 2	1,10 ± 0,02	100 ± 3	65 ± 3	20 ± 10
8	Continuously dry	50 ± 2	1,10 ± 0,02	100 ± 3	Not controlled	Not controlled

Figure 11. Exposure cycles using daylight filters and window glass filters [40]

Exposure cycles of the xenon arc are described in Figure 11. In the experimental part of this work, Method A was used.

7.2.2 Devices with xenon arc

There are different kinds of designs of the xenon weathering instruments. Specimens can be exposed in vertical or in horizontal position, and there can be two-tier or three-tier inclined specimen racks. [26, p.43] The design which was used in the experimental part of this thesis was Xenon Weather-Ometer Ci4000, with a water-cooling system.

The water-cooled xenon arc system is placed in the middle of a nearly spherical basket-like specimen rack. The lamp is surrounded by two cylindrical optical filters. Cooling water flows in between the xenon arc, the inner filter and an outer filter. In addition to its cooling function, the water absorbs some of the unwanted near infrared radiation. [22, p.157; 26, p.43]

Figure 12. Positioning of test specimens in the Ci4000 Xenon Weather-o-meter

The xenon lamp, which is described in chapter 7.2.3, is located in the middle of the specimen rack. The entire specimen rack rotates around the xenon lamp continuously at a low speed. As can be seen in Figure 12, the test panels are arranged vertically on three tiers inside the specimen rack. Through this type of positioning, only the test panels in the middle of the three tiers are exactly vertical when facing the xenon lamp. The test panels on the other tiers face the lamp at an angle. [22, p.158; 26, p.43]

7.2.3 Xenon arc

The xenon arc is a precision gas discharge lamp in a quartz tube. The arc is surrounded by two cylindrical optical filters; an inner filter and an outer filter (Figure 13). Through the filtering, the spectral power distribution is changed to simulate solar radiation. [26, p.41; 22, p.118]

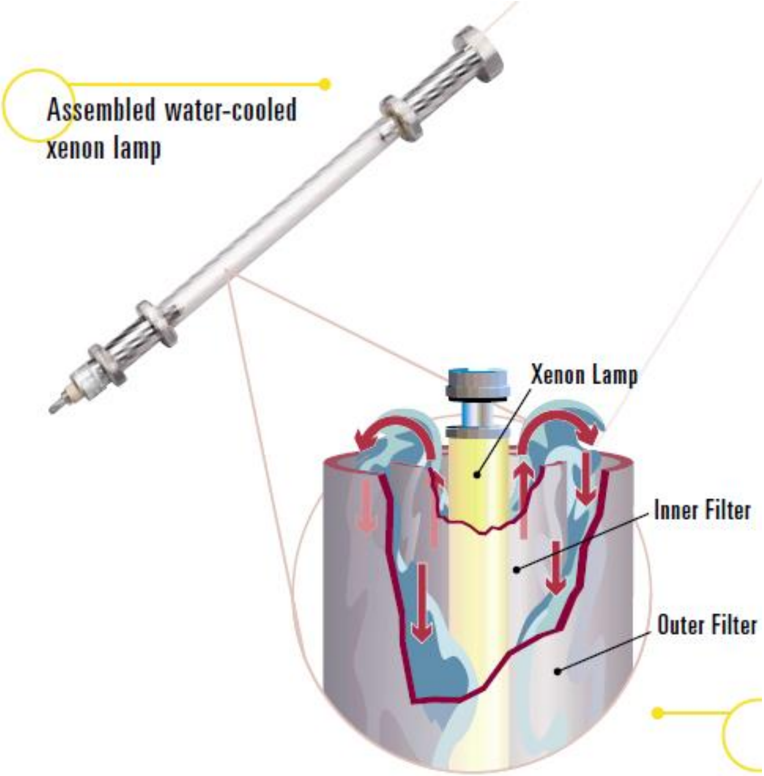


Figure 13. Structure of the xenon arc and its cooling system [26, p.43]

Changing the filters around the arc, it is possible to create the conditions that correspond either to direct sunlight or light coming through the glass. The arc has to be replaced after 1200 hours of burning. [22, p.158]

7.2.4 Filters

The xenon arc uses filters to achieve the appropriate spectral distribution that simulates different conditions of natural weathering and special testing requirements. Combination of filters is required to reduce unwanted radiation. Different filter types allow for varying amounts of shortwave UV, which can significantly affect the speed and type of degradation. Two commonly used types of filters are outdoor sunlight or sunlight filtered through window glass. Figure 14 shows the spectral power distribution of sunlight compared to a xenon arc with daylight and sunlight behind the glass compared to a xenon arc with a window filter. [39, p.12-5; 26, p.44]

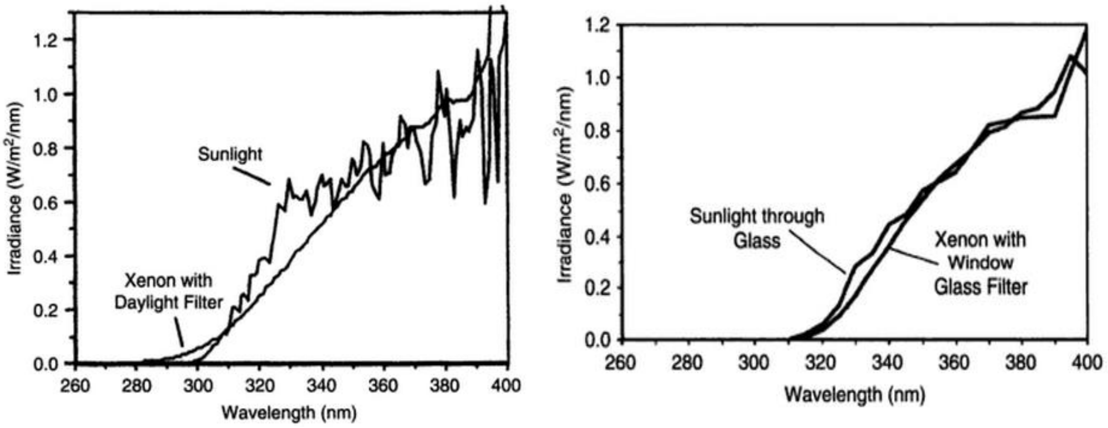


Figure 14. Xenon arc with daylight filter and window glass filter [39, p.12-6]

In order to simulate daylight, filters should be used to remove short-wavelength UV radiation. Filters to minimize irradiance at wavelengths shorter than 310 nm should be used to simulate daylight through window glass. In addition, filters to remove infrared radiation may be used to prevent unrealistic heating of the specimens, which can cause thermal degradation not experienced during outdoor exposures. [40]

Experimental part

8 Objective of the experimental part

The objective of this experimental part was to test the influence of different solar reflective black pigments on the durability of wooden substrates. In addition, the objective was to determine the efficiency of the IR-reflective pigments in limiting the heat build-up of different wood finishes. The test methods consisted of accelerated weathering tests, surface temperature measurements and color change measurements.

9 Test methods

9.1 Surface temperature measuring instrument

The measuring instrument of surface temperature was built in the laboratory of Tikkurila Oyj. The purpose of the surface temperature measuring instrument was to simulate solar irradiance and its effect on the surface temperature of pigmented topcoats.

The surface temperature measurement equipment consisted of a halogen lamp (1000 Watt) and infrared thermometer, which is described in more detail below. Figure 15 summarizes the measuring instrument.

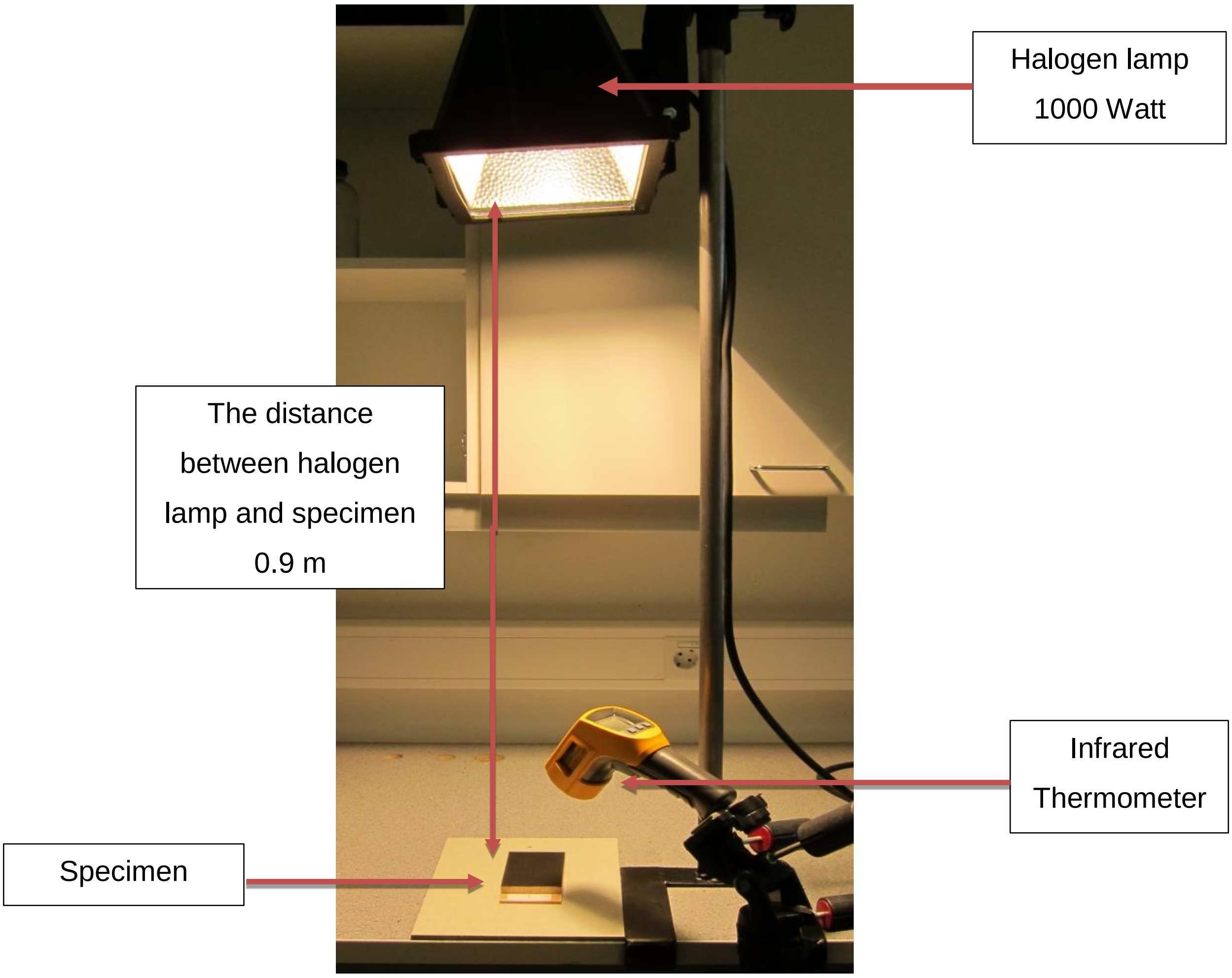
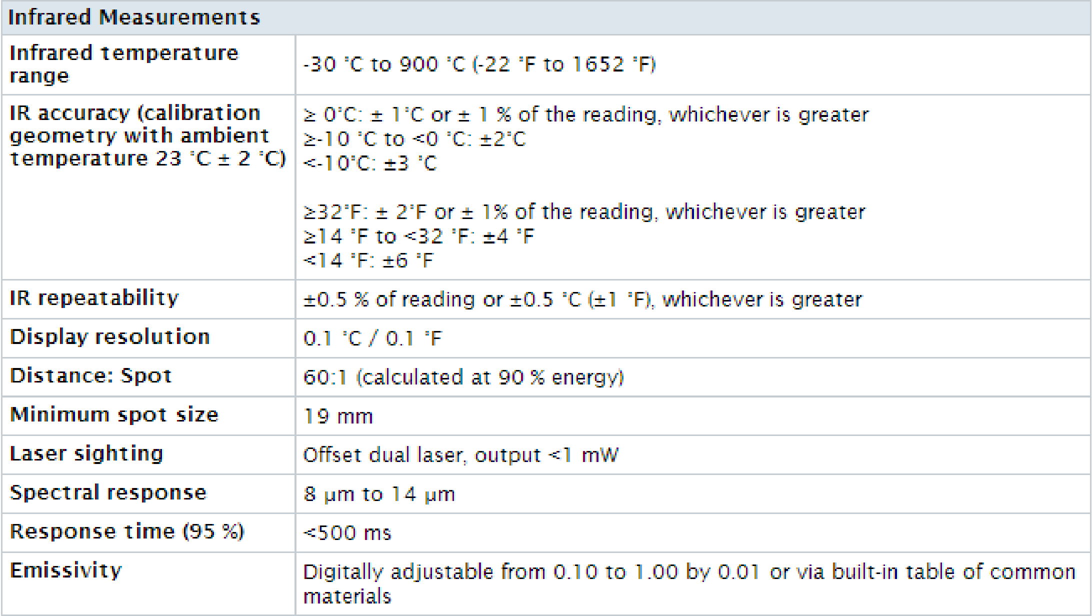


Figure 15. Surface temperature measuring instrument

The surface temperature of a pigmented sample was increased by exposure to a halogen lamp (1000 Watt) from a distance of 0.9 m. The test specimen was placed below the halogen lamp. Two different exposure times were used. The specimens of product A and D were tested using two hours exposure time, whereas specimens of product B and C were exposed for two hours and cooled for one hour (lamp on for 2 hours, cooling for 1 hour). The initial temperature was kept as close as possible to 24 °C in the beginning of every measurement, to minimize any distortion of the results.

An infrared thermometer was used for measuring the surface temperature of the specimens. The infrared thermometer was the model Fluke 572-2 Infrared Thermometer. The specifications of this meter can be found in Figure 16.

The infrared thermometer is designed for non-contact temperature measurement. It determines the surface temperature of an object by measuring the amount of infrared energy radiated by the surface of the object. [43]



Infrared Measurements	
Infrared temperature range	-30 °C to 900 °C (-22 °F to 1652 °F)
IR accuracy (calibration geometry with ambient temperature 23 °C ± 2 °C)	≥ 0°C: ± 1°C or ± 1 % of the reading, whichever is greater ≥-10 °C to <0 °C: ±2°C <-10°C: ±3 °C ≥32°F: ± 2°F or ± 1% of the reading, whichever is greater ≥14 °F to <32 °F: ±4 °F <14 °F: ±6 °F
IR repeatability	±0.5 % of reading or ±0.5 °C (±1 °F), whichever is greater
Display resolution	0.1 °C / 0.1 °F
Distance: Spot	60:1 (calculated at 90 % energy)
Minimum spot size	19 mm
Laser sighting	Offset dual laser, output <1 mW
Spectral response	8 µm to 14 µm
Response time (95 %)	<500 ms
Emissivity	Digitally adjustable from 0.10 to 1.00 by 0.01 or via built-in table of common materials

Figure 16. Specifications of the infrared thermometer

The difference between replicates in the temperature measurement was tested by making three measurements for the same specimen (A1 and A2).

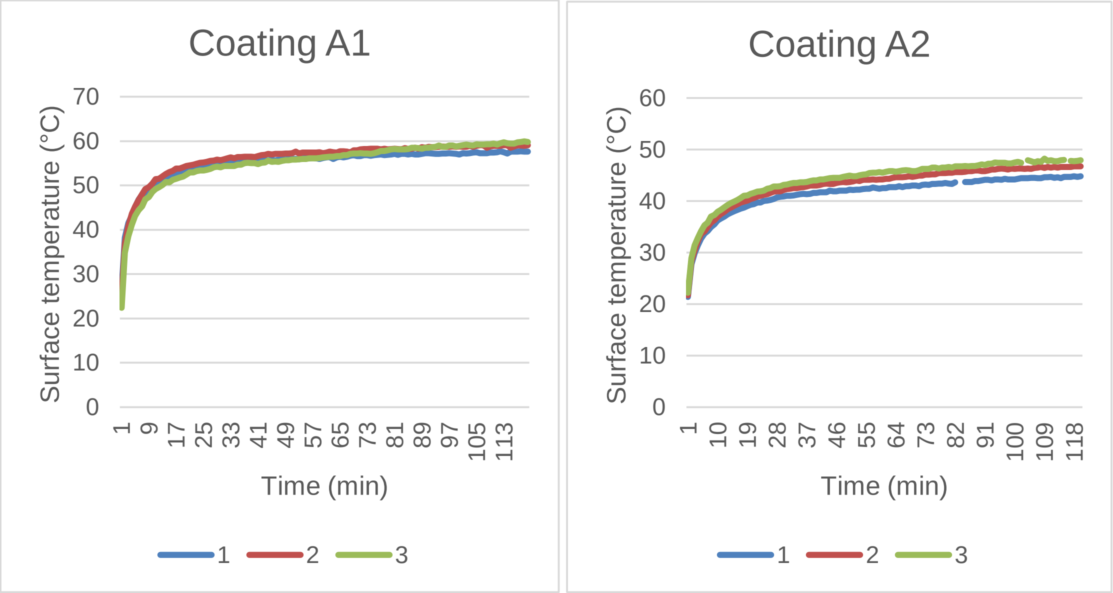


Figure 17. Difference between replicates in surface temperature measurement (A1 and A2)

According to the repeated measurements, the difference between replicates of the measurement was estimated to be ±1°C as can been seen in Figure 17.

9.2 Accelerated tests

The specimens were tested in the Xenon Ci4000 Weather-Ometer. Before testing, specimens were numbered and photographed. Specimen sizes were adapted to fit the device specific holders. The back and the other sides except the front side of specimens were treated with a varnish. Two replicate samples per coating were tested and a set of unexposed samples was kept as reference controls.

The exposure tests were carried out according to standard ISO 4892-2:2006: Plastics – Methods of exposure to laboratory light sources – Part 2: Xenon- arc lamps. This experiment consisted of the test cycles of UV irradiation and water spray in order to simulate natural weathering.

As discussed in chapter 7.2.2, when the test panels are arranged vertically on three tiers inside the specimen rack, only the test panels in the middle of the three tiers are exactly vertical when facing the xenon arc. Therefore, the places of the specimens groups were changed every week.

Table 2. Rating scheme for designating the quantity and size of cracks [44]

Rating	Quantity of cracks	Rating	Size of cracks
0	none, i.e. no detectable cracks	0	not visible under x10 magnification
1	very few, i.e. small, barely significant number of cracks	1	only visible magnification up to x10
2	few, i.e. small but significant number of cracks	2	just visible with normal corrected vision
3	moderate number of cracks	3	clearly visible with normal corrected vision
4	considerable number of cracks	4	large cracks generally up to 1 mm wide
5	dense pattern of cracks	5	very large cracks generally more than 1mm wide

Quantity and size of cracks were evaluated according to the scheme of standard ISO 4628-4 (Table 2). The specimens were also assessed visually compared to the unexposed specimens. More detailed visual evaluations can be found in Appendix 3.

Table 3. Visual evaluations

Abbreviation	Explanation	Degree	Explanation
Y	Yellowing	1	Very slight
G	Greying	2	Moderate
C	Chalking	3	Severe
B	Bleeding		
D	Dirt on a surface		

The visual evaluations were assessed according to Table 3. The single letter on the left side refers to the explanation of what kind of damages were seen in exposed specimens during the accelerated weathering. On the right side is the degree of damage. In addition, the specimens were photographed weekly.

9.3 Color measurement

The color change of the exposed specimens was measured using a HunterLab MiniScan XE portable spectrophotometer. Technical information about this instrument can be found in Table 4. The purpose of the color measurements was to get numerical values of the color change when the specimens were exposed in an accelerated weathering test.

Color changes were measured after certain times of exposure during the xenon test. The color change of the specimens was measured by comparing the unexposed reference specimens to the exposed specimens. Three measurements were taken from different places of the specimen and the meter calculated the average values of all values measured.

Table 4. Technical information about HunterLab MiniScan color measurement [45]

Name	HunterLab MiniScan XE
Spectral range/ resolution/ bandwidth	400-700nm/ 10nm /12nm
Wavelength Accuracy	1nm
Photometric Range	0-150 %
Photometric Resolution	0.1 %
Standards	ISO 7724: Part 1: Paints and varnishes – Colorimetry Part 2: Color measurement Part 3: Calculation of color differences

10 Tests

10.1 Products used in this work

The wood finishes in this study were different types of waterborne exterior wood finishes. These wood finishes are introduced in Table 5. Table 6 describes the colorants which were tested in this experiment. Wood finishes and colorant trade names are coded.

The colorants were added to four different waterborne wood finishes. There were nine different colorants including two different reference colorants carbon black and iron oxide. The wood finishes are called A, B, C and D and colorants are denoted from 1 to 9. Wood finishes A and B were commercial products and wood finishes C and D were prepared in the laboratory.

Table 5.Wood finishes used in the tests

Product	**Type**	**Binder**	**Density (kg/l)**	**Solid volume (%)**	**Note**
A	Wood oil	Alkyd	1.01	22	Semitrans-parent
B	Wood stain	Alkyd + acrylate	1.01	21	Semitrans-parent
C	Film forming stain	Alkyd + acrylate	1.02	30	Semitrans-parent
D	Opaque paint	Acrylate	1.12	47	Opaque

Table 6. Colorants used in test formulation

Sample	Pigment Index	Chemistry	System	Colourant / Pigment	Notes
1	PBk7	inorganic	Universal	Colorant	Reference (carbon black)
2	PG17	inorganic	Waterborne	Colorant	
3	PBk11	inorganic	Universal	Colorant	Reference (iron oxide)
4	PBr29	inorganic	Waterborne	Colorant	
5	PBr29	inorganic	Waterborne	Colorant	
6	PBk32	organic	Waterborne	Colorant	
7	PBr29	inorganic	Waterborne	Easy dispersible pigment	
8	PG17	inorganic	Universal	Easy dispersible pigment	
9	PG17	inorganic	Universal	Colorant	

In the tests below, all the coatings are called by their code names. For example A1 refers to the coating which includes product A and colorant 1.

10.2 Preliminary tests

10.2.1 Experiment

The aim of the preliminary tests was to verify the suitability of colorants in the selected products and make them comparable with the reference, carbon black. The purpose was to eliminate colorants from the study which were not compatible for the wood finish. In preliminary tests, only wood finish A was used and each colorant was tested together in it.

The preliminary tests were started by preparing two samples of each colorant. Two different volume concentrations were used; 3.5 vol-% and 7 vol-%. The samples were divided into two jars and they were mixed for 2 min and 4 min. After that the samples were drawn-down with applicator. It was noticed that there was no difference in color between these two mixing times. Therefore it was concluded that all these colorants are compatible with the examined product and no colorants was eliminated.

However, according to the first tests, the IR-reflective pigments were not comparable by their color intensity with the reference, carbon black. As a result, the samples were made more comparable by searching the nearest possible color intensity, by changing the volume concentrations of the samples.

Preliminary tests were also carried out to measure the efficiency of the surface temperature measurement equipment. The measurement equipment was tested to find out suitable initial temperatures for measurements and total measurement time. Two different specimens (A1 and A7) with two different volume concentrations and uncoated wood were tested. These two colorants (A1 and A7) were chosen to be tested in preliminary tests because it was assumed that they behave differently when concerning the heat build-up. The chosen volume concentrations are reported in Table 7.

Table 7. Volume concentrations used in preliminary tests

Specimen	**Concentration (vol-%)**
A1	0.1
A1	3.5
A7	0.1
A7	5
Blank wood	-

In addition, different volume concentrations were tested in coating A7 to verify the suitable volume concentration for the final tests. These volume concentrations are reported in Table 8.

Table 8. Different volume concentrations of A7

Specimen	**Concentration (vol-%)**
A7	0.1
A7	0.3
A7	0.5
A7	2
A7	5

Figure 18 demonstrates the tested specimens. These specimens were exposed to the halogen lamp for approximately 30 minutes. The target was to see if there would be a big difference in heat build-up, using different volume concentrations.

Figure 18. Coating A7 with different volume concentrations (0.1vol-%, 0.3 vol-%, 0.5 vol-%, 2 vol-%, 5 vol-%)

10.2.2 Preliminary test results

As already mentioned in chapter 9.1.1, there were no differences between the two mixing times: 2 min and 4 min. Therefore one mixing time (2min) was chosen for the final tests.

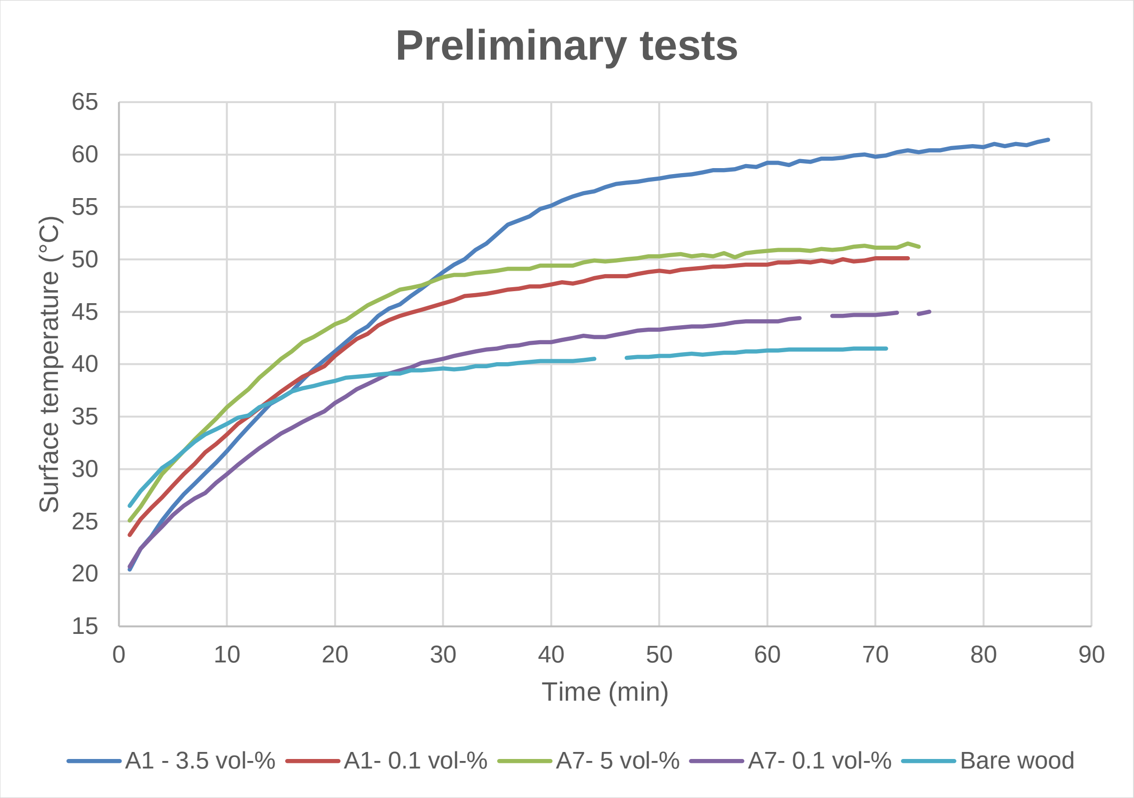


Figure 19. Surface temperature measurements in preliminary tests

Figure 19 shows that the surface temperature of bare wood does not increase as much as coated specimens, when exposed to the halogen lamp. Surface temperatures of the specimens with bigger volume concentrations increased more. It was also discovered that the starting temperature of the measurement may affect the heat build-up of the specimen.

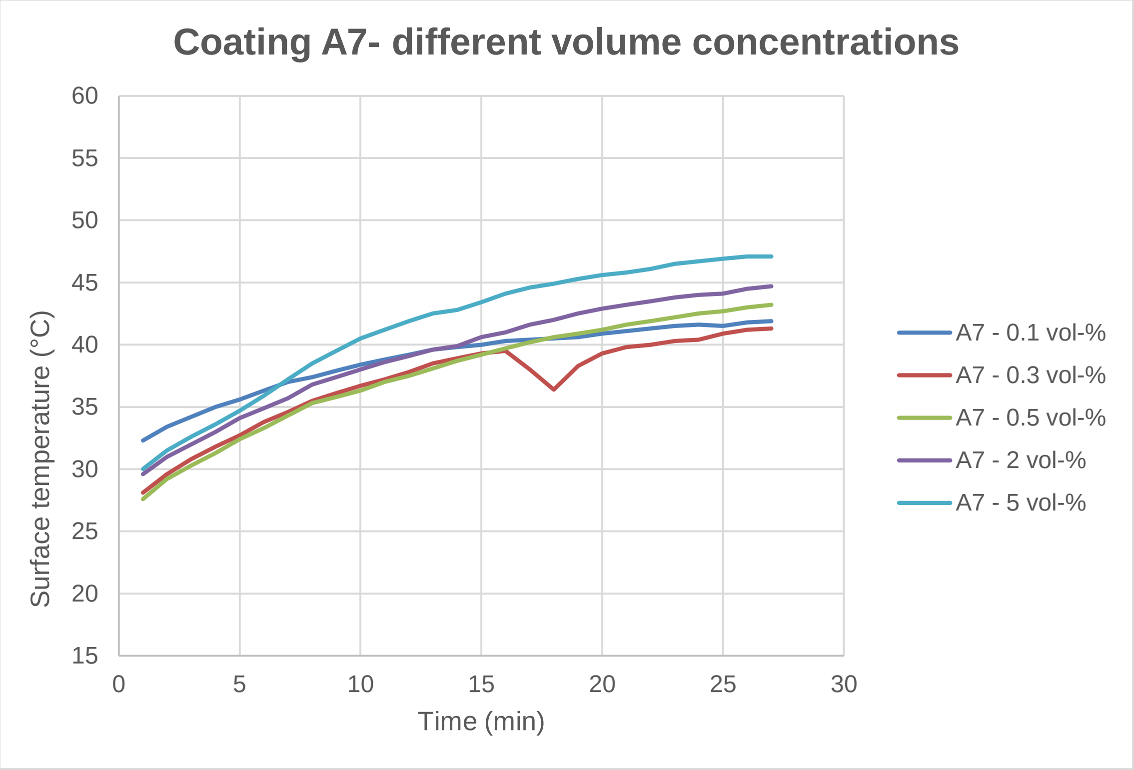


Figure 20. Surface temperature measurement of A7 with different volume concentrations

On the basis of surface temperature measurements, it was observed that the different volume concentrations make a great difference in the heat build-up on the surface of the specimen. The difference in surface temperature increase between these five different volume concentrations was significant (Figure 20.). However, since the time for this experiment was limited, only one volume concentration was chosen for the tests. For semitransparent products (A, B, C), the volume concentration in the middle (0.5 vol-%) was chosen. For opaque paint (D), the volume concentration 3.5 was chosen on the basis of the volume concentration which is normally used in opaque paints.

10.3 Tests

10.3.1 Sample preparation

On the basis of the results from the preliminary tests, the suitable volume concentrations were chosen and samples were prepared. The samples were prepared in two deciliter glass jars. Every jar was filled up to 90 %. The samples were mixed with a shaker for two minutes and left to stand until the next day. The chosen volume concentrations are reported in Appendix 1.

10.3.2 Specimen preparation

The test coatings were applied on a pine substrate. The specimens were 100 mm x 65 mm x 10 mm (L x W x T).

Each coating was applied on three wood specimens; two parallel specimens for the accelerated weathering tests, and one unexposed specimen was made for reference control. The reference specimen is called 1 and the parallel, exposed specimens are called 1A and 1B. The unexposed reference specimen was also used for the surface temperature measurements. The total number of the samples was 108.

Test coatings were applied on the substrate twice, without any primer. The coating was applied on to the substrate with a brush and left to dry for five days. The amount of coating applied was weighed and the dry film thicknesses of the coatings were calculated using the following formula (1) below. Calculated dry film thicknesses of formulations can be found in Appendix 2.

$$\text{Thickness}_{\text{dry}}\ (\mu\text{m}) = \frac{Volume\ (L)}{Area\ (m2)} \text{ x } \frac{1000}{1} \text{ x } \frac{NVVt}{100} \qquad (1)$$

NVV_T = non-volatile (%) [42, p.1181]

10.3.3 Specimen evaluation

The samples were taken out of the accelerated weathering test weekly and evaluated according to standard ISO 4628: “Evaluation of degradation of coatings - Designation of quantity and size of defects, and of intensity of uniform changes in appearance.” The standard includes evaluations of cracking, blistering, flaking and chalking. Specimens were visually assessed to the unexposed reference specimen. In addition, specimens were photographed weekly.

11 Results and discussion

11.1 Infrared Thermometer results

Figure 21 shows the surface temperature results of coating A. The surface temperature of the samples with the IR-reflective colorants increased approximately 10 °C less than those of the references, carbon black and iron oxide.

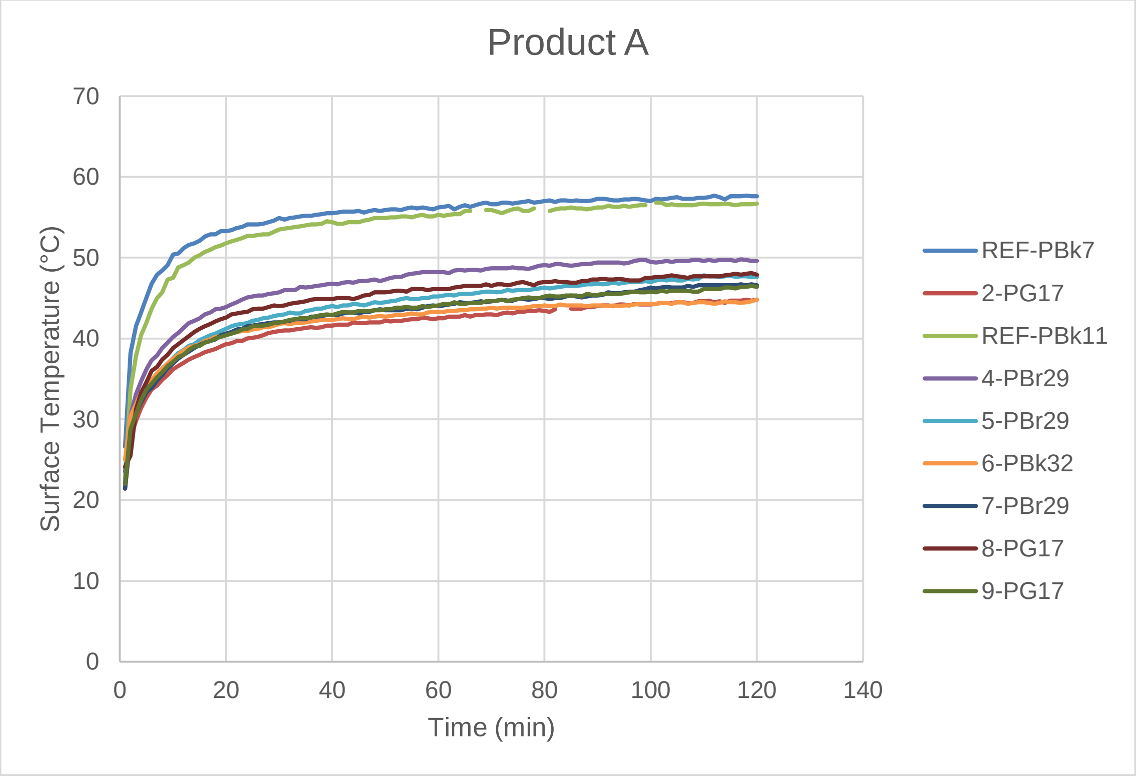


Figure 21. Surface temperature measurements of coating A

The maximum temperatures of the specimens, after two hours of exposure, were recorded. Maximum temperatures of the samples with IR-reflective colorants were compared to the reference with carbon black (PBk7). Table 9 shows the cooling effect of the IR-reflective colorants compared to the reference carbon black. According to these results, colorants 2 (PG17) and 6 (PBk32) reduced the surface temperature of the specimen the most, and colorant 4 (PBr29) reduced the surface temperature of the specimen the least.

Table 9. The cooling effect of solar reflective colorants compared to the reference carbon black

Pigment Index	Colorant	Temperature (max) (°C) after 2 hours exposure	Cooling effect (°C)
PBk 7	1	57.6	
PBk 11	3	56.7	
PG 17	2	44.8	-12.8
PG 17	8	47.9	-9.7
PG 17	9	46.4	-11.2
PBr 29	4	49.6	-8
PBr 29	5	47.6	-10
PBr 29	7	46.6	-11
PBk 32	6	44.8	-12.8

The specimens with coating B were exposed for two hours and cooled for one hour. The cooling time was tested to see how fast the surface temperature decreases after exposure. According to Figure 22 the temperature difference between the IR-reflective colorants and the references was approximately 13 °C.

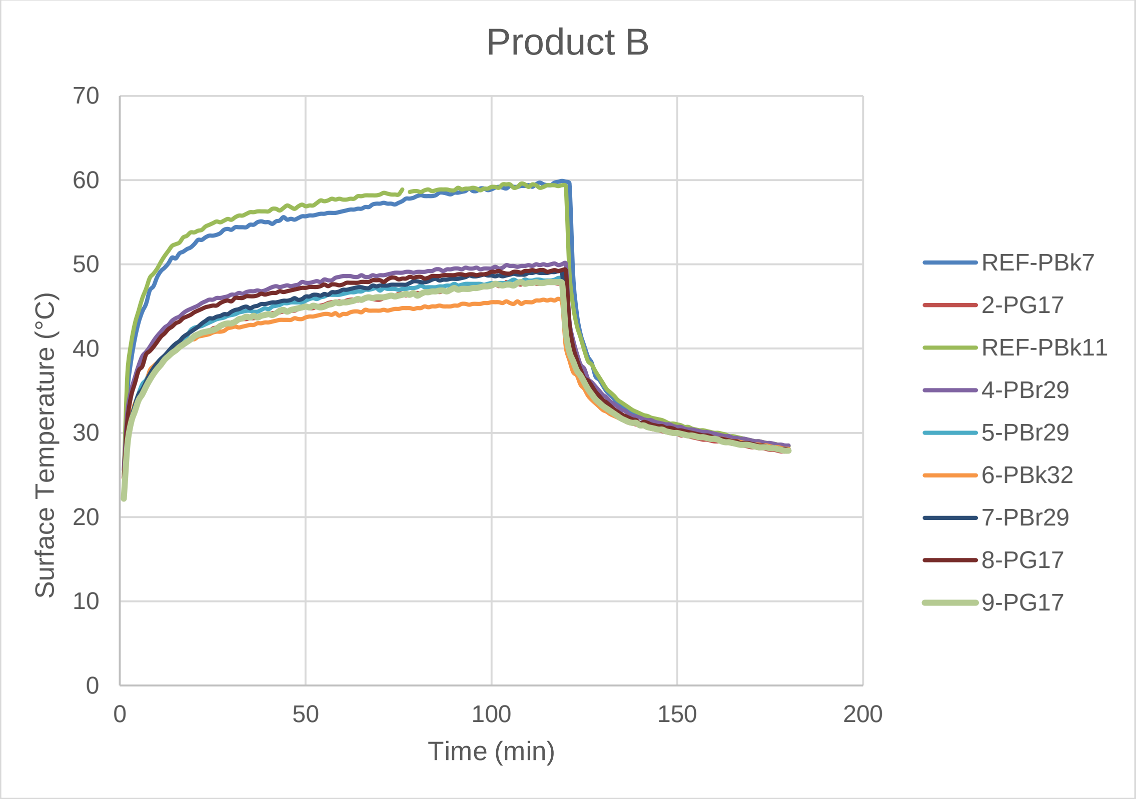


Figure 22. Surface temperature measurements of coating B

The cooling effect of the IR-reflective colorants in coating B appeared to be slightly higher than compared to IR-reflective colorants in coating A. As can be seen from the Table 10 below, the cooling effect of colorant 6 (PBk32) and 7 (PBr29), compared to reference 1 (PBk7) was almost -20 °C. Colorant 4 (PBr29) showed the least cooling effect.

Table 10. The cooling effect of solar reflective colorants compared to the reference carbon black

Pigment Index	**Colorant**	**Temperature (max) (°C) after 2 hours exposure**	**Cooling effect (°C)**
PBk 7	1	59.8	
PBk 11	3	59.3	
PG 17	2	47.9	-11.9
PG 17	8	49.3	-10.5
PG 17	9	46.4	-13.4
PBr 29	4	50.1	-9.7
PBr 29	5	48.3	-11.5
PBr 29	7	42.7	-17.1
PBk 32	6	40.2	-19.6

The specimens with coating C were also exposed to a halogen lamp for two hours and cooled for one hour. The results (Figure 23.) show that the IR-reflective colorants reduced the heat build-up on the surface of the specimen approximately 10 °C, compared to the reference colorants.

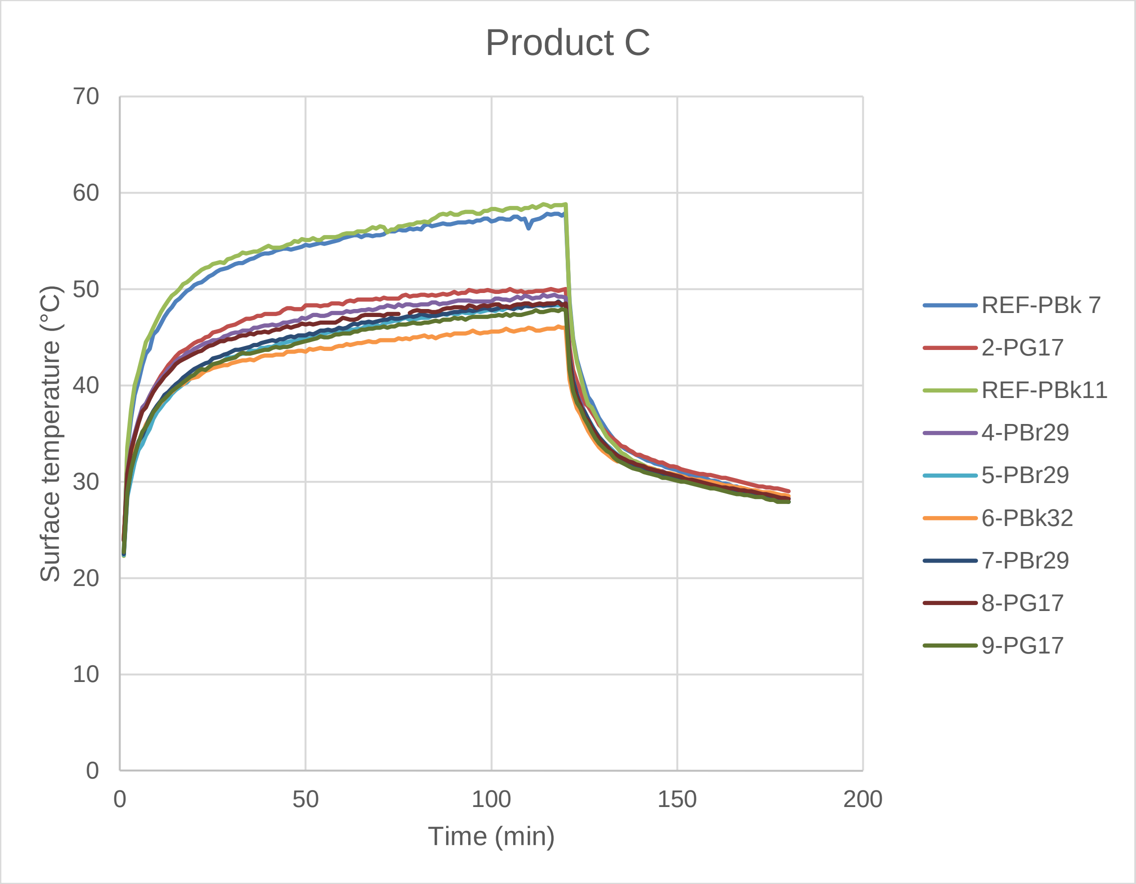


Figure 23. Surface temperature measurements of coating C

Table 11 presents the cooling effect of IR-reflective colorants with coating C. The cooling effect of colorant 6 (PBk32) and colorant 9 (PG17) was the best, and colorant 2 (PG17) was the least able to reduce the surface temperature of the specimen.

Table 11. The cooling effect of solar reflective colorants compared to the reference carbon black

Pigment Index	**Colorant**	**Temperature (max) (°C) after 2 hours exposure**	**Cooling effect (°C)**
PBk 7	1	58.0	
PBk 11	3	58.8	
PG 17	2	50	-8
PG 17	8	48.5	-9.5
PG 17	9	47.8	-10,2
PBr 29	4	49.1	-8.9
PBr 29	5	48.4	-9.6
PBr 29	7	48.4	-9.6
PBk 32	6	46	-12

The surface temperature, generally, for coating D, rose more than the other coatings. As can be seen in Figure 24, the surface temperature difference between the reference colorants and IR-reflective colorants is approximately 13 °C.

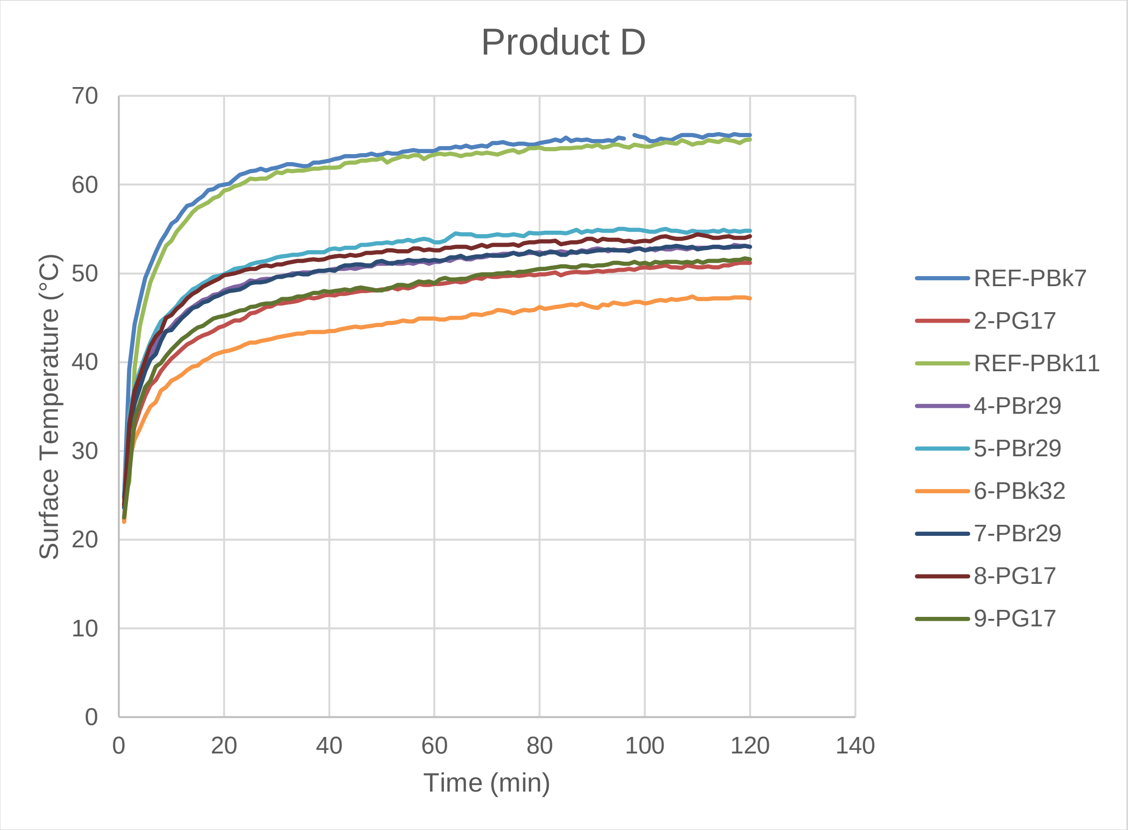


Figure 24. Surface temperature measurements of coating D

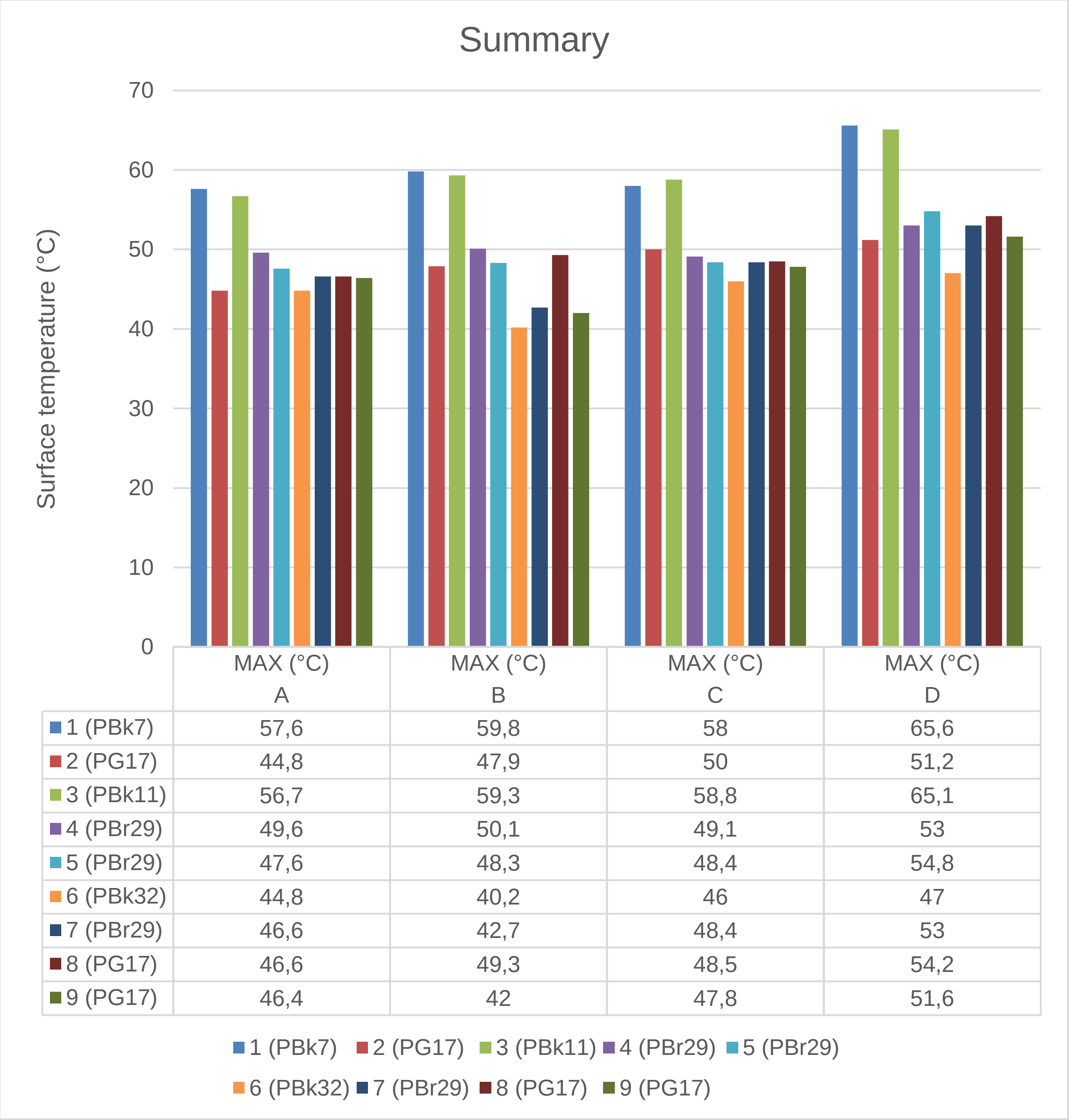
The cooling effect of the IR-reflective colorants in coating D are shown in Table 12. Colorant 6 (PBk32) reduced the surface temperature of the specimen the most, and colorant 5 (PBr29) reduced the surface temperature of the specimen the least, compared to the reference colorant, carbon black.

Table 12. Cooling effect of the solar reflective colorants compared to reference carbon black (D)

Pigment Index	Colorant	Temperature (max) (°C) after 2 hour exposure	Cooling effect (°C)
PBk 7	1	65,6	
PBk 11	3	65,1	
PG 17	2	51,2	-14,4
PG 17	8	54,2	-11,4
PG 17	9	51,6	-14
PBr 29	4	53	-12,6
PBr 29	5	54,8	-10,8
PBr 29	7	53	-12,6
PBk 32	6	47	-18,6

Surface temperature measurements of reference colorants and IR-reflective colorants indicate that all of the IR-reflective colorants were able to decrease the heat build-up compared to the reference colorants.

For more detailed comparison between the heat build-up results, the maximum temperatures and the cooling effects, compared to the reference colorants, are reported in Figure 25.



	MAX (°C) A	MAX (°C) B	MAX (°C) C	MAX (°C) D
1 (PBk7)	57,6	59,8	58	65,6
2 (PG17)	44,8	47,9	50	51,2
3 (PBk11)	56,7	59,3	58,8	65,1
4 (PBr29)	49,6	50,1	49,1	53
5 (PBr29)	47,6	48,3	48,4	54,8
6 (PBk32)	44,8	40,2	46	47
7 (PBr29)	46,6	42,7	48,4	53
8 (PG17)	46,6	49,3	48,5	54,2
9 (PG17)	46,4	42	47,8	51,6

Figure 25. Summary of all the surface temperature measurements

All of these wood finishes can not be compared with each other when it comes to the heat build-up due to their different properties. The opaque paint (D) showed slightly more heat build-up compared to the other wood finishes. This can be explained with the fact that the opaque paint absorbs the solar radiation more than the other wood finishes (A, B, C) which were semitransparent.

The surface temperature of reference colorants carbon black and iron oxide increased close to each other. When the different pigment indices are considered, perylene black (PBk32) showed the best result in limiting the heat build-up effect on the surface.

Pigment greens (PG17) generally showed slightly less heat build-up, compared to pigment browns (PBr29).

Generally, when comparing the IR-reflective colorants to each other, colorants 6 (PBk32), 7 (PBr29) and 9 (PG17) were the best limiting the heat build-up on the coating surface. On the contrary, colorants 8 (PG17) and 4 (PBr29) were the worst limiting the heat build-up on the coating surface.

11.2 Accelerated test results

The color changes which were discovered during the exposure in accelerated tests can be identified by comparing the exposed specimens to the unexposed specimens. The pictures can be found in Appendix 4, Appendix 5, Appendix 6 and Appendix 7. The pictures are divided according to their pigment indices. The picture which is taken before the exposure is always above. In some pictures the unexposed reference specimen is in the middle of the two exposed specimens.

Exposed specimens were assessed according to standard ISO 4628-4 which includes the evaluations of cracking, blistering, flaking and chalking. However, only cracking was noticed from the specimens during the weathering.

Specimens with coating A were tested in an accelerated weathering test for five weeks. After one week of exposure, only very slight yellowing and cracking could be seen in specimens. Specimens started to crack more after three weeks of exposure and specimens started also to turn gray. After five weeks of exposure, the test was interrupted because almost all of the specimens were badly cracked and grayed. The pictures of specimens with coating A can be found in Appendix 4.

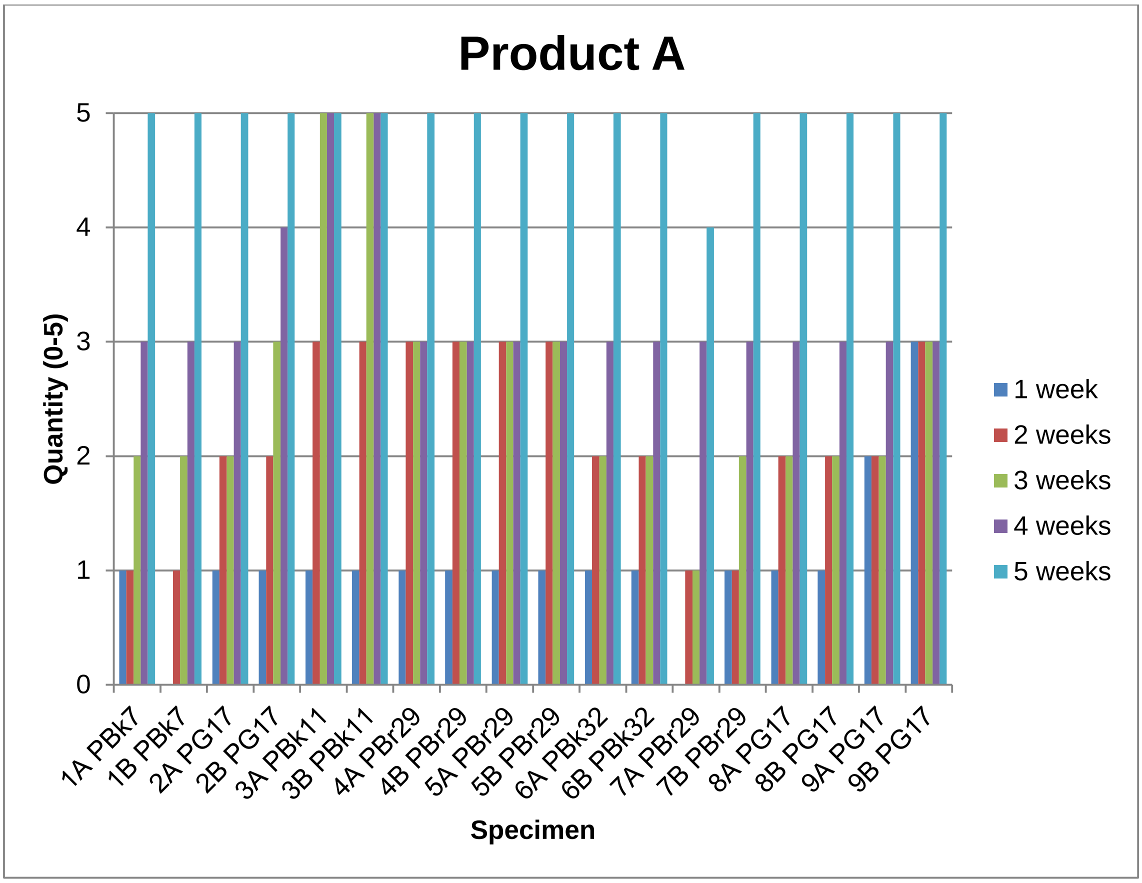


Figure 26. Evaluation of cracking in coating A

The results of cracking in coating A are shown in Figure 26. There were no major differences between the IR-reflective colorants pigment indices PG17, PBr29 and PBk32. On the basis of these results the reference carbon black (PBk7) was the best and the other reference iron oxide (PBk11) was the worst. When it comes to the IR-reflective colorants, colorant 7 (PBr29) and 8 (PG17) showed the best results. Both were easily dispersible pigments.

Specimens with coating B were tested in an accelerated weathering test for five weeks. Specimens with coating B behaved similarly to coating A. After one week of exposure specimens started to yellow, after three weeks specimens started to crack and turn grey and after five week exposure, almost all of the specimens were badly cracked and the test was interrupted. The pictures of specimens with coating B can be found in Appendix 5.

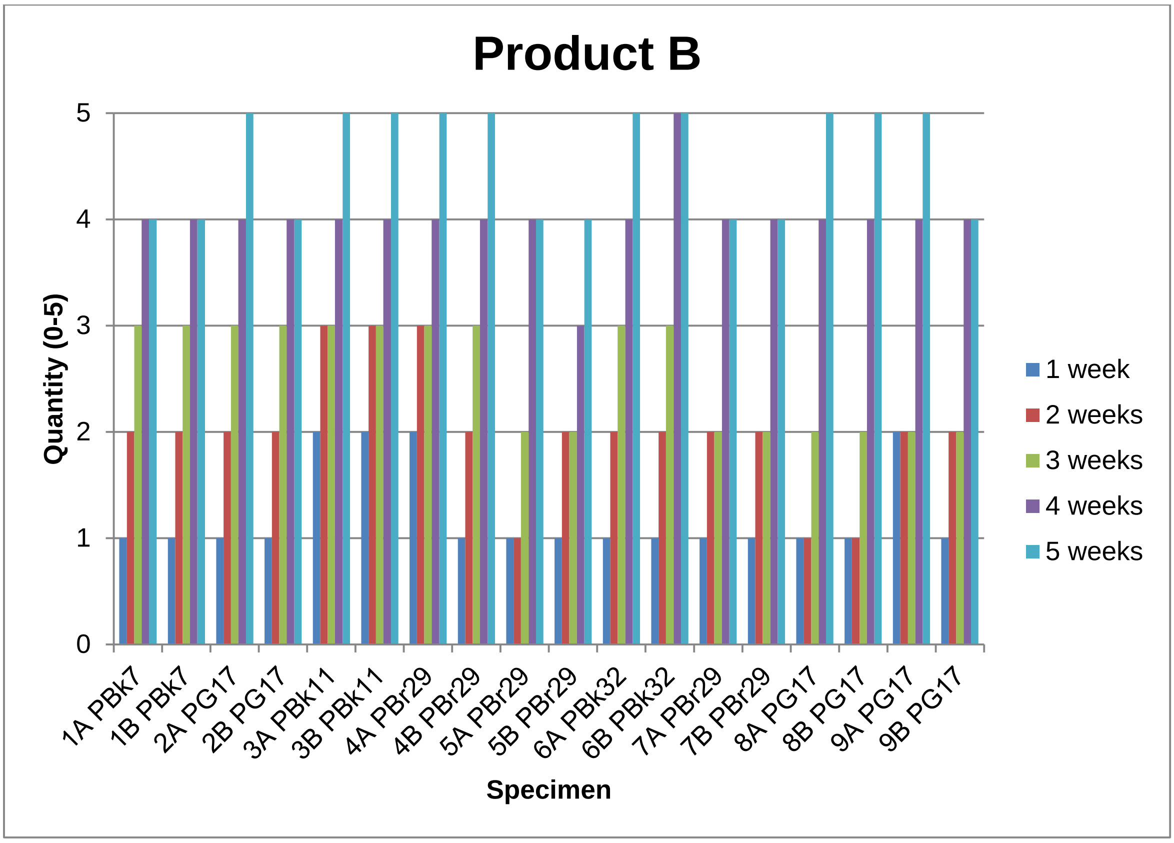


Figure 27. Evaluation of cracking in coating B

The results of cracking are showed in Figure 27. Colorants 1 (PBk7), 7 (PBr29) and 8 (PG17) showed least cracking and colorants 3 (PBk11) and 6 (PBk32) cracked the most during the accelerated weathering.

Since the time for this experiment was limited, specimens with coating C were exposed in accelerated weathering test for only three weeks. After one week of exposure the specimens started to yellow but not much cracking appeared in the specimens. After three weeks of exposure the color change of the specimens was significant. The pictures of specimens with coating C can be found in Appendix 6.

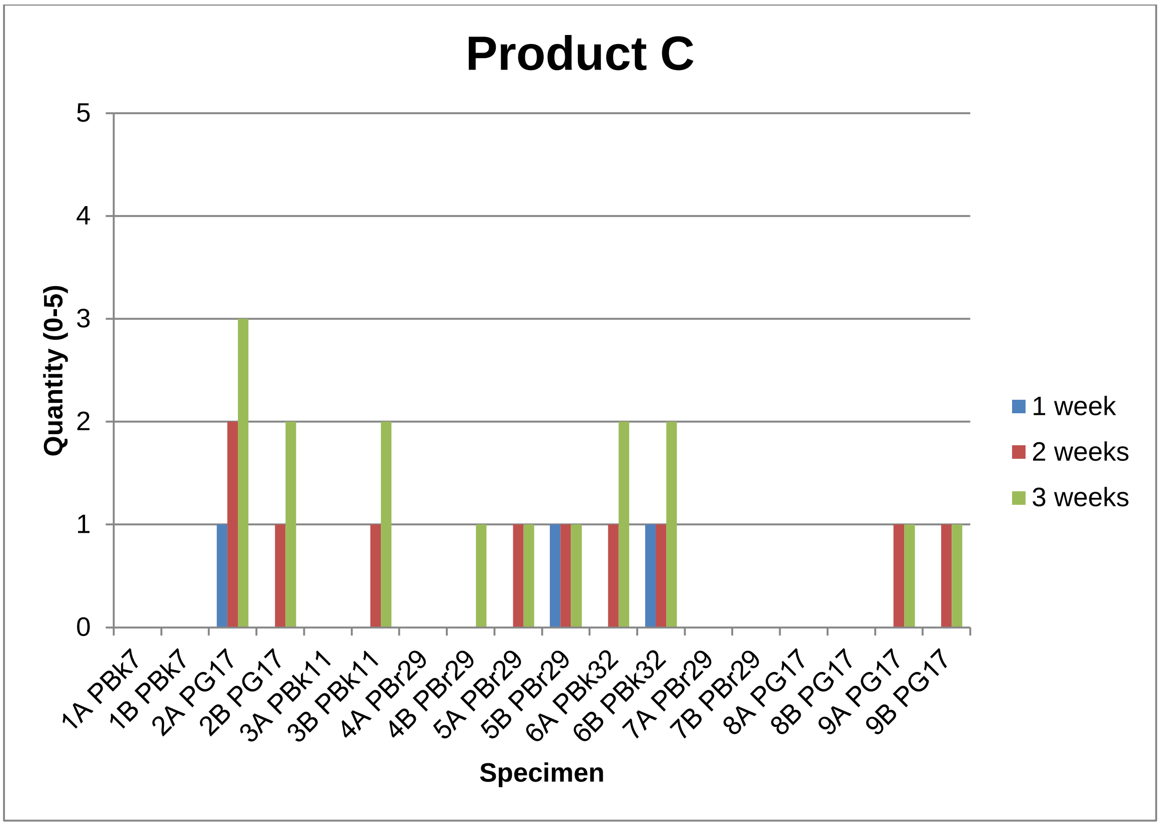


Figure 28. Evaluation of cracking in coating C

During the three weeks of exposure the specimens with coating C cracked only slightly compared to specimens with coating A and B. Colorant 2 (PG17) cracked the most and colorants 1 (PBk7), 7 (PBr29) and 8 (PG17) did not cracked at all, as shown in Figure 28.

Specimens with coating D were tested in an accelerated weathering test for seven weeks. There were no specific changes in specimens during the first four weeks of exposure. However, after five weeks specimens started to chalk and after seven weeks of exposure, almost all of the specimens were chalked and the test was stopped. The pictures of specimens with coating D can be found in Appendix 7.

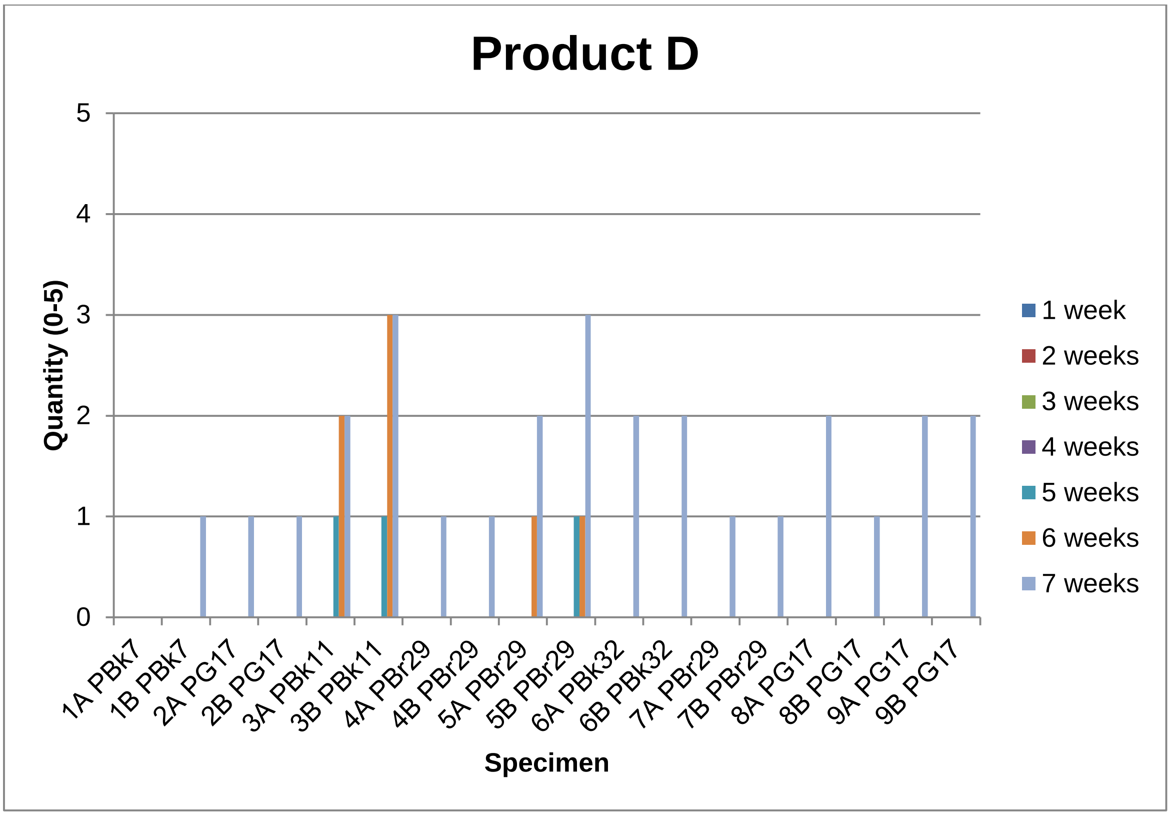


Figure 29. Evaluation of cracking in coating D

There were no specific changes in cracking during the seven weeks exposure as shown in Figure 29. Only specimens 3 (PBk11) and 5 (PBr29) showed slight changes in cracking after five weeks. Other specimens started to slightly crack after seven weeks of exposure.

When the specimens were assessed during the accelerated weathering test, it was noticed that the reference colorant carbon black (PBk7) showed very good results in every coating whereas other reference iron oxide (PBk11) showed the worst results of all the colorants during the accelerated weathering test. However, the poor weather resistance of colorant 3 (PBk11) can be explained by what was already discussed in chapter 4.2.2: “Iron oxide pigments used in paint films tend to undergo surface degradation when exposed to the weathering elements, leading to reduced gloss, chalking, and a slight change in color.” [2, p.134]

When considering the differences between the pigment indices of IR-reflective colorants, the results were slightly disconnected. Pigments browns (PBr29) generally showed slightly better results during the accelerated weathering test, compared to pigment greens (PG17). Specimens with pigment brown cracked slightly less and discoloration was lower. Perylene black (PBk32) cracked and discolored in semitransparent coatings (A, B and C), but it showed good results in the opaque paint (D).

When analyzing the overview of all the coatings and colorants, colorants 1 (PBk7), 7 (PBr29) and 8 (PG17) showed the best results in accelerated weathering tests. During the accelerated weathering test their color change was very slight in almost every coating, and with coating D they chalked as much as the other specimens. In addition, the chalking of these specimens was slight.

11.3 Color measurement results

Color measurements were made in order to measure the difference between the different coatings after the accelerated weathering test. A computer software calculated average values of three measurements. The results of color measurement can be found in Appendix 8. The table includes the standard values measured from unexposed specimens, total lightness change DL*, change in redness Da* and change in blueness Db*. Because there is no significant differences in the Da* values, only values of DL* and Db* were examined. As reported in chapter 5.2.1, a low value in DL* means darkness whereas a big value means lightness, b- means blueness, b+ is yellowness, a- means greenness and a+ is redness.

Color measurement were made to specimens with coating A after five weeks of exposure in the accelerated weathering test. There was no significant change in lightness in specimens 1 (PBk7), 6 (PBk32) and 8 (PG17). Specimens 2 (PG17), 3 (PBk11), 4 (PBrk29), and 9 (PG17) turned lighter during the exposure and specimen 7 (PBr29) was darkened during the weathering. When it comes to the blueness change, all the specimens became more blue.

Color measurements were made to specimens with coating B after five weeks of exposure in the accelerated weathering test. All the specimens turned lighter and became more blue during the accelerated weathering testing.

Color measurement were made to specimens with coating C after one week of exposure in accelerated weathering test. After one week of exposure, all the specimens of coating C were darkened and yellowed significantly.

Color measurements were made to specimens with the coating D after six weeks of exposure in accelerated weathering test. Specimens with coating D showed more scattering between the colorants. There were no major color changes in the reference colorants 1 (PBk7) and 3 (PBk11). Colorant 6 (PBk32) also kept its color. Colorants 2 (PG17), 4 (PBr29), 7 (PBr29), 8 (PG17) and 9 (PG17) turned lighter. Colorant 5 (PBr29) discolored significantly. There were also changes in the blueness. Colorant 1 (PBk7), 7 (PBr29) and 8 (PG17) yellowed and other colorants became more blue.

The color measurements were made to get more information about the color change of the specimens. The results, however, are only approximate, because the color measurements from specimens of coating A and B were taken after five weeks of exposure in accelerated tests. Some of the specimens were badly discolored and the protective ability of the paint film was diminished.

12 Summary and Conclusions

The purpose of this thesis was to study how solar reflective black pigments affect coating degradation on wooden substrates. In addition, the aim was to determine the efficiency of the solar reflective black pigments in limiting the heat build-up of different types of wood finishes.

As already discussed in the theoretical part, it is known that objects with light colors tend to reflect heat, and stay relatively cool to touch when exposed to the sun. Conversely, dark surfaces tend to absorb heat with a subsequent temperature increase. In addition, substantial variations of temperature expose pigmented wooden substrates to a massive stress. High temperatures and UV radiation cause premature ageing of the surface and shorten the lifetime of the coating. The main purpose of solar reflective pigments is to keep the coated item cooler and improve the durability of the coating.

In the experimental part, the influence of the solar reflective black pigments on the durability of wood coating was tested in the accelerated weathering test. The effectiveness of the solar reflective black pigments was tested using the surface temperature measurements, where the test specimens were exposed to the halogen lamp. In addition, the color change measurements were made. Four different wood finishes were tested; one opaque paint and three semitransparent wood finishes. They were called A, B, C and D. The colorants which were tested were two reference colorants, carbon black (PBk7), iron oxide (Pbk11), and seven different IR-reflective colorants of three different pigment indices; chromium oxide green (PG17), chromium iron brown (PBr29) and perylene black (PBk32). The colorants were denoted from 1 to 9.

The primary advantage of using the solar reflective coatings is to reflect a significant amount of solar radiation from the colored surfaces to keep them cooler. The test results confirm that replacing the standard black colorants (PBk7 and PBk11) with IR-reflective colorants cause less heat build-up on the surface. All the tested IR-reflective colorants were able to decrease the heat build-up approximately 10 °C compared to the reference colorants. The test results provided that perylene black (PBk32) showed the best result of limiting the heat build-up effect on the coating surface. Pigment green (PG17) showed generally less heat build-up compared to pigment brown (PBr29). This can be explained by the fact that pigment green (PG17) has higher reflectance in infrared light and it should be more effective in limiting the heat build-up in the coating surface. Generally, when the IR-reflective colorants were compared to each other, the coatings with colorants 6 (PBk32) and 9 (PG17) were able to limit the heat build-up on the coating surface the most. On the contrary, the coatings with colorants 8 (PG17) and 4 (PBr29) limited the heat-build up on the coating surface the least.

High temperatures and UV radiation cause premature ageing of the surface and shorten the lifetime of the coating. Another advantage of solar reflective colorants is to keep the coated substrate cooler and thus improve the durability of the coating. The accelerated weathering tests were used to test the durability of coatings pigmented with IR-reflective colorants. The accelerated weathering test showed that performance of the coating was dependent on the color indices of the pigments. The coatings with pigment brown (PBr29) showed slightly better results in the accelerated weathering test compared to the coatings with pigment green (PG17). The coatings with pigment brown did not crack as much as coatings with pigment green and its color retention was better during the accelerated weathering test. Perylene black (PBk32) showed good results in opaque paint (D) but in the semitransparent products (A, B, C) the coatings with perylene black cracked and discolored heavily during the accelerated weathering test. Generally, when considering the damages and discoloration of the coating film during the accelerated weathering test, coatings with colorant 7 (PBr29) and colorant 8 (PG17) cracked and discolored the least whereas coatings with colorant 5 (PBr29) cracked and discolored the most.

Comparison between the IR-reflective colorants in the different wood finishes was difficult due to the different properties of the wood finishes. It was found, that some of the colorants were good in some wood finishes but did not perform at all in some of the wood finishes. When comparing the results the colorant 6 (PBk32) was the best in the opaque paint (PBk32) both in the surface temperature measurement test and in the accelerated weathering test. The colorant 7 (PBr29) showed the best results in the semitransparent products (A, B, C). Although the coatings with colorant 7 (PBr29) were not the best in limiting the heat build-up of the coating surfaces, it was one of the best and in the accelerated weathering test the coatings with colorant 7 (PBr29) were the most durable.

It was noticed during the accelerated weathering test that the reference colorant, carbon black (PBk7) showed very good results whereas the other reference colorant, iron oxide

(PBk11) showed the worst results of all the colorants. These results confirm the theoretical facts. According to the theory, carbon black has excellent light and weathering stability and outstanding depth and intensity of color, whereas paint films with iron oxide pigments tend to undergo surface degradation when exposed to weathering, leading to reduced gloss, chalking, and a slight change in color.

Even though the IR-reflective colorants were able the limit the heat build-up of the coatings surface, their durability, however, was not as good as the coatings with carbon black. The coatings with carbon black (PBk7), have excellent light and weathering stability and they gave more hiding power in the semitransparent wood finishes (A, B, C) and thus preventing degradation processes. Because the hiding power of the coatings with different colorants was not the same, this factor makes it more difficult to compare the differences between the colorants. In addition, the comparison between the inorganic and organic colorants is not necessarily the best way due to the different properties of these two pigment families.

Although the study has successfully demonstrated that all the tested IR-reflective colorants were able to decrease the heat build-up on the coating surface and some of the colorants showed good results in the accelerated weathering test, it has certain limitations in terms of the statistical reliability of the experiment. Since the time for the experimental part was limited, it was not possible to repeat all of the tests. However, it can be stated that comparing the surface temperature measurement results made in this experiment to the results of the experiment showed in chapter 4.1 are very similar. The experiment in chapter 4.1 showed that replacing the standard black pigments (PBk7 and PBk11) with chromium iron brown (PBr29) decreased the heat build-up approximately 10 °C. The results found in this experiment are very similar and it can be stated that these results increased the reliability of the surface temperature measurement.

When considering the further studies, there are a few factors that should be examined. In the preliminary tests, it was observed that the different volume concentrations caused great differences in the heat build-up in the surface of the specimens. Additional tests from different volume concentrations would help to clarify the differences between the colorants. In addition, the surface temperature change of the specimens during the accelerated weathering testing would be interesting to examine.

In conclusion, the results suggest that it is important to test the colorants properties for the different types of wood finishes. The colorant has to be chosen on the basis of the compatibility with the particular type of wood finish. Information and results found in this thesis are useful and will provide the basis for the further research. The results can be utilized in the company’s future development activities.

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Selected volume concentrations

This Appendix includes the chosen volume concentrations of the coatings.

Product	**A**	**B**	**C**	**D**
Sample	**Volume concentration (vol-%)**			
1	0.5	0.5	0.5	3.4
2	0.7	0.7	0.7	3.2
3	1	1	1	3.3
4	1	1	1	3.2
5	1.4	1.4	1.4	5
6	0.7	0.7	0.7	3.4
7	0.5	0.5	0.5	3
8	0.3	0.3	0.3	3
9	1.3	1.3	1.3	5

Dry film thicknesses of wood finishes

This Appendix includes the amount of applied coating and calculated dry film thicknesses.

Product A

Specimen	Specimen weight in the beginning (g)	1st layer (g)	2nd layer (g)	In total (g)	Calculated dry film thickness (µm)
1	47.20	0.52	0.44	0.96	29
1A	50.64	0.49	0.44	0.93	28
1B	52.93	0.51	0.39	0.90	27
2	48.55	0.51	0.5	1.01	31
2A	49.99	0.52	0.51	1.03	31
2B	49.98	0.52	0.46	0.98	30
3	46.65	0.55	0.46	1.01	31
3A	49.29	0.47	0.46	0.93	28
3B	48.43	0.45	0.47	0.92	28
4	45.99	0.51	0.46	0.97	34
4A	48.12	0.53	0.46	0.99	31
4B	50.24	0.48	0.48	0.96	32
5	51.39	0.60	0.45	1.05	32
5A	50.71	0.52	0.48	1.00	34
5B	49.75	0.52	0.43	0.95	31
6	50.49	0.53	0.43	0.96	29
6A	51.26	0.54	0.42	0.96	29
6B	51.21	0.53	0.42	0.95	29
7	49.54	0.51	0.43	0.94	29
7A	57.82	0.55	0.42	0.97	30
7B	50.68	0.53	0.41	0.94	29
8	49.26	0.54	0.42	0.96	29
8A	53.48	0.49	0.41	0.90	27
8B	52.05	0.49	0.43	0.92	28
9	45.12	0.61	0.45	1.06	32
9A	54.19	0.52	0.40	0.92	28
9B	53.27	0.51	0.39	0.90	27

Product B

Specimen	Specimen weight in the beginning (g)	1st layer (g)	2nd layer (g)	In total (g)	Calculated dry film thickness (μm)
1	44.63	0.53	0.49	1.02	29
1A	60.95	0.53	0.44	0.97	29
1B	58.97	0.51	0.45	0.96	28
2	45.63	0.58	0.54	1.12	33
2A	59.19	0.57	0.44	1.01	29
2B	54.19	0.53	0.45	0.98	28
3	49.86	0.58	0.48	1.06	31
3A	53.40	0.59	0.46	1.05	31
3B	53.57	0.46	0.42	0.88	26
4	49.27	0.58	0.50	1.08	31
4A	66.72	0.56	0.44	1.00	29
4B	50.15	0.56	0.45	1.01	29
5	48.32	0.56	0.56	1.12	33
5A	52.29	0.60	0.47	1.07	31
5B	57.18	0.53	0.49	1.02	30
6	45.99	0.59	0.51	1.10	32
6A	61.41	0.51	0.47	0.98	28
6B	61.94	0.53	0.47	1.00	30
7	51.42	0.57	0.53	1.10	32
7A	61.20	0.54	0.49	1.03	30
7B	60.44	0.52	0.47	0.99	29
8	46.74	0.64	0.51	1.15	33
8A	58.42	0.55	0.46	1.01	29
8B	50.47	0.57	0.46	1.03	30
9	49.58	0.58	0.48	1.06	31
9A	49.06	0.55	0.53	1.08	31
9B	58.15	0.64	0.47	1.11	32

Product C

Specimen	Specimen weight in the beginning (g)	1st layer (g)	2nd layer (g)	In total (g)	Calculated dry film thickness (µm)
1	55.58	0.48	0.42	0.90	37
1A	68.90	0.49	0.56	1.05	43
1B	53.89	0.53	0.45	0.98	41
2	54.13	0.56	0.45	1.01	41
2A	58.18	0.50	0.42	0.92	38
2B	62.07	0.50	0.43	0.93	38
3	50.26	0.53	0.43	0.96	39
3A	51.40	0.56	0.41	0.97	40
3B	51.60	0.52	0.46	0.98	40
4	47.82	0.49	0.45	0.94	39
4A	52.41	0.52	0.45	0.97	40
4B	50.71	0.57	0.44	1.01	41
5	55.90	0.56	0.49	1.05	43
5A	51.63	0.55	0.44	0.99	40
5B	61.75	0.54	0.41	0.95	39
6	47.55	0.56	0.43	0.99	41
6A	61.81	0.51	0.48	0.99	41
6B	61.29	0.52	0.48	1.00	41
7	56.95	0.54	0.44	0.98	40
7A	64.00	0.55	0.39	0.94	39
7B	70.97	0.52	0.42	0.94	39
8	48.14	0.57	0.42	0.99	41
8A	53.53	0.56	0.42	0.98	40
8B	63.63	0.56	0.42	0.98	40
9	50.87	0.57	0.44	1.01	41
9A	55.49	0.52	0.47	0.99	41
9B	68.96	0.50	0.54	1.04	43

Product D

Specimen	Specimen weight in the beginning (g)	1st layer (g)	2nd layer (g)	In total (g)	Calculated dry film thickness (µm)
1	47.91	0.43	0.31	0.74	43
1A	47.79	0.57	0.28	0.85	50
1B	49.07	0.41	0.29	0.70	41
2	47.75	0.39	0.29	0.68	40
2A	48.34	0.50	0.27	0.77	45
2B	50.00	0.55	0.27	0.82	48
3	48.87	0.40	0.34	0.74	43
3A	54.37	0.52	0.27	0.79	46
3B	47.77	0.44	0.28	0.72	42
4	48.66	0.39	0.29	0.68	40
4A	46.88	0.52	0.26	0.78	46
4B	46.09	0.49	0.22	0.71	42
5	49.44	0.51	0.47	0.98	58
5A	56.40	0.55	0.48	1.03	60
5B	72.26	0.47	0.41	0.88	52
6	45.98	0.40	0.46	0.86	50
6A	62.46	0.55	0.35	0.90	53
6B	55.97	0.50	0.27	0.77	45
7	49.09	0.43	0.42	0.85	50
7A	59.62	0.47	0.34	0.81	48
7B	54.30	0.44	0.30	0.74	43
8	50.51	0.39	0.31	0.70	41
8A	55.87	0.45	0.29	0.74	43
8B	51.24	0.46	0.28	0.74	43
9	48.63	0.55	0.21	0.76	45
9A	50.70	0.47	0.37	0.84	49
9B	51.42	0.45	0.36	0.81	48

Evaluation of accelerated weathering tests

A	1 week (161,8 h)			2 weeks (327,5 h)			3 weeks (409,2 h)			4 weeks (637,2 h)			5 weeks (799,7 h)		
Specimen	**Quantity**	**size**	**notes**	**Quantity**	**size**	**notes**	**Quantity**	**size**	**notes**	**Quantity**	**size**	**notes**	**Quantity**	**size**	**notes**
1 (PBk7)	0	-		1	1		2	2		3	2		3	2	
1A	1	2	Y1	1	1	G1	2	2	G2	3	2	G2	5	5	G3
1B	0	-	Y1	1	1	G1 / A	2	1	G2	3	2	G2	5	5	G3
2 (PG17)	0	-		3	1		3	2		3	2		3	3	
2A	1	2	Y1	2	2	G1	2	2	G2	3	2	G3	5	5	G3
2B	1	2	Y1	2	2	G1	3	2	G2	4	2	G3	5	5	G3
3 (PBk11)	0	-		2	1		2	1		3	2		3	2	
3A	1	1	Y1	3	4	G1	5	4	G2	5	5	G2	5	5	G3
3B	1	1	Y1	3	4	G1	5	4	G2	5	5	G2	5	5	G3
4 (PBr29)	0	-		0	-		1	1		3	2		3	2	
4A	1	1	Y1	3	2	G1	3	2	G1	3	2	G2	5	4	G3
4B	1	1	Y1	3	1	G1	3	2	G1	3	2	G2	5	5	G3
5 (PBr29)	1	1		4	1		4	2		4	2		4	2	
5A	1	1	Y1	3	1	G1	3	2	G3	3	2	G3	5	4	G3
5B	1	1	Y1	3	1	G1	3	2	G3	3	2	G3	5	4	G3
6 (PBk32)	1	1		3	1		3	2		3	2		3	2	
6A	1	1	Y1	2	1	G2	2	1	G3	3	2	G3	5	5	G3
6B	1	1	Y1	2	1	G2	2	1	G3	3	2	G3	5	5	G3
7 (PBr29)	1	1		2	2		3	3		3	2		3	2	
7A	0	-		1	1	G1	1	1	G1	3	2	G2	4	4	G2
7B	1	1		1	1	G1	2	1	G1	3	3	G2	5	5	G2
8 (PG17)	2	1		3	2		3	2		3	2		3	2	
8A	1	1	Y1	2	1	G1	2	2	G2	3	3	G2	5	5	G3
8B	1	1	Y1	2	1	G1	2	2	G2	3	3	G2	5	5	G3
9 (PG17)	0	-		1	1		1	1		2	2		2	2	
9A	2	1	Y1	2	1	Y3 / G1	2	2	G3	3	3	G3	5	5	G3
9B	3	1	Y1	3	1	Y3 / G1	3	2	G3	3	3	G3	5	5	G3

Notes: Y= Yellowing, G= Greying, C=Chalking, B=Bleeding, D=Dirt on a surface, 1= Very slight, 2= Moderate, 3= Severe

B	1 week (165,7 h)			2 weeks (328,4 h)			3 weeks (475,4 h)			4 weeks (637,9 h)			5 weeks (799,3 h)		
Specimen	**Quantity**	**size**	**notes**	**Quantity**	**size**	**notes**	**Quantity**	**size**	**notes**	**Quantity**	**size**	**notes**	**Quantity**	**size**	**notes**
1 (PBk7)	3	2		3	2		3	2		3	2		3	2	
1A	1	1	Y1	2	2	G1	3	2	G2	4	4	G2	4	4	G3
1B	1	1	Y1	2	1	G1	3	2	G2	4	4	G2	4	5	G3
2 (PG17)	3	2		3	2		3	2		3	2		3	2	
2A	1	1	Y1	2	1	G2	3	2	G3	4	4	G3	5	5	G3
2B	1	1	Y1	2	1	G2	3	2	G3	4	3	G3	4	4	G3
3 (PBk11)	3	2		3	2		3	2		3	2		3	2	
3A	2	1	Y2	3	4	G1	3	4	G2	4	4	G3	5	4	G3
3B	2	2	Y2	3	4	G1	3	4	G2	4	4	G3	5	4	G3
4 (PBr29)	3	2		3	2		3	2		3	2		3	2	
4A	2	1	Y1	3	1	G1	3	2	G2	4	3	G2	5	4	G3
4B	1	1	Y1	2	1	G1	3	3	G2	4	3	G3	5	3	G3
5 (PBr29)	3	1		3	1		3	1		3	2		3	2	
5A	1	1	Y2	1	1	G2	3	1	G3	4	3	G3	4	4	G3
5B	1	1	Y2	2	1	G2	3	1	G3	3	3	G3	4	4	G3
6 (PBk32)	2	1		3	1		3	2		3	2		3	2	
6A	1	1	Y2	2	1	G3	3	1	G3	4	3	G3	5	3	G3
6B	1	1	Y2	2	1	G3	3	1	G3	5	4	G3	5	5	G3
7 (PBr29)	3	1		3	2		3	2		3	2		3	2	
7A	1	1	Y1	2	2	G1	2	3	G2	4	4	G3	4	4	G3
7B	1	1	Y1	2	2	G1	2	3	G2	4	3	G3	4	4	G3
8 (PG17)	2	2		2	2		3	2		3	2		3	2	
8A	1	1	Y1	1	1	G2	2	2	G2	4	4	G3	5	4	G3
8B	1	1	Y1	1	1	G2	2	2	G2	4	4	G3	5	4	G3
9 (PG17)	2	1		2	1		2	2		2	2		2	2	
9A	2	1	Y2	2	2	G3	2	2	G3	4	4	G3	5	4	G3
9B	1	1	Y2	2	2	G3	2	2	G3	4	4	G3	4	4	G3

Notes: Y= Yellowing, G= Greying, C=Chalking, B=Bleeding, D=Dirt on a surface, 1= Very slight, 2= Moderate, 3= Severe

C	1 week (161,4 h)			2 weeks (305,5 h)			3 weeks (469,9h)		
Specimen	Quantity	size	notes	Quantity	size	notes	Quantity	size	notes
1 (PBk7)	0	-		0	-		0	-	
1A	0	-	Y1	0	-	Y2	0	-	A1
1B	0	-	Y1	0	-	Y2	0	-	A1
2 (PG17)	1	1		1	1		1	1	
2A	1	1	Y2	2	2	A	3	5	A3
2B	0	-	Y2	1	1	A	2	2	A3
3 (PBk11)	1	1		1	1		1	1	
3A	0	-	Y2	0	-	A	0	1	A2
3B	0	-	Y2	1	1	A	2	1	A2
4 (PBr29)	0	-		0	-		0	-	
4A	0	-	Y1	0	-	Y2	0	-	A1
4B	0	-	Y1	0	-	Y2	1	1	A1
5 (PBr29)	1	1		1	1		1	1	
5A	0	-	Y2	1	1	Y3	1	1	A2
5B	1	1	Y2	1	1	Y3	1	1	A2
6 (PBk32)	1	1		2	1		2	1	
6A	0		Y2	1	1	Y3	2	2	A2
6B	1	1	Y2	1	1	Y3	2	2	A2
7 (PBr29)	1	1		1	1		1	1	
7A	0	-	Y1	0	-	Y1	0	-	A1
7B	0	-	Y1	0	-	Y1	0	-	A1
8 (PG17)	1	1		1	1		1	1	
8A	0	-	Y1	0	-	Y2	0	-	A2
8B	0	-	Y1	0	-	Y2	0	-	A2
9 (PG17)	0	-		1	1		1	1	
9A	0	-	Y1	1	1	D	1	1	A2
9B	0	-	Y1	1	1	D	1	1	A2

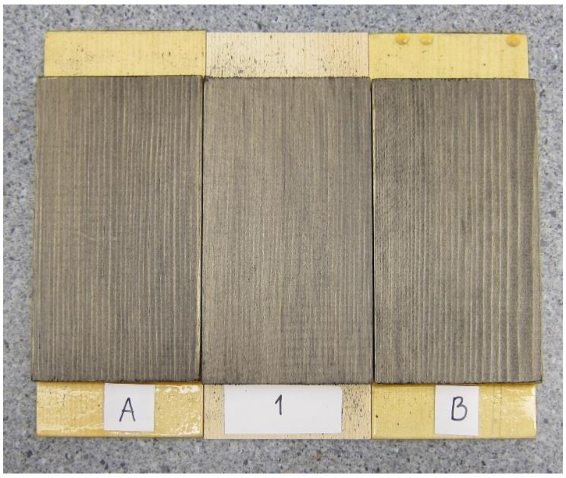
Notes: Y= Yellowing, G= Greying, C=Chalking, B=Bleeding, D=Dirt on a surface, 1= Very slight, 2= Moderate, 3= Severe

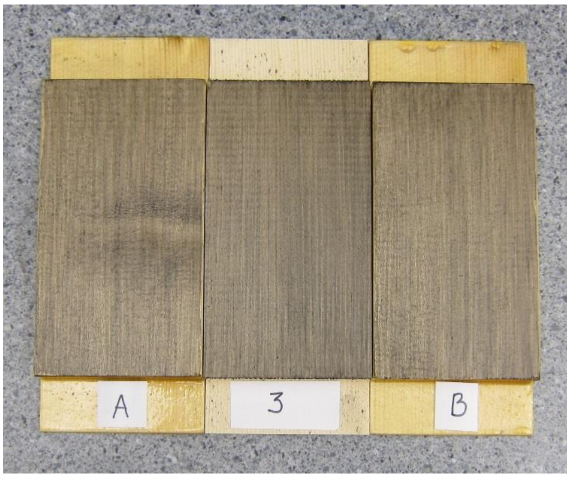
D	1 week (161,8 h)			2 weeks (327,5 h)			3 weeks (409,2 h)			4 weeks (637,2 h)			5 weeks (799,7 h)			6 weeks (961,1 h)			7 weeks (1105,2 h)		
Specimen	**Quantity**	**size**	**notes**	**Quantity**	**size**	**notes**	**Quantity**	**size**	**notes**	**Quantity**	**size**	**notes**	**Quantity**	**size**	**notes**	**Quantity**	**size**	**notes**	**Quantity**	**size**	**notes**
1 (PBk7)	0	-		0	-		0	-		0	-		0	-		0	-		0	-	
1A	0	-		0	-		0	-		0	-		0	-		0	-	C1	0	-	C2
1B	0	-		0	-		0	-		0	-		0	-		0	-	C1	1	1	C2
2 (PG17)	0	-		0	-		0	-		0	-		0	-		0	-		0	-	
2A	0	-		0	-		0	-		0	-		0	-	C2	0	-	C3	1	1	C2
2B	0	-		0	-	B1	0	-	B2	0	-	B3	0	-	C1 / B3	0	-	C3 /B3	1	1	C2/B3
3 (PBk11)	0	-		0	-		0	-		0	-		0	-		0	-		1	1	
3A	0	-		0	-		0	-		0	-	B1	1	1	C1 / B1	2	1	C2/B1	2	2	C3/B3
3B	0	-		0	-	B1	0	-	B1	0	-	B3	1	2	C1 /B3	3	2	C2/B3	3	2	C3/B3
4 (PBr29)	0	-		0	-		0	-		0	-		0	-		0	-		0	-	
4A	0	-		0	-		0	-		0	-		0	-	C1	0	-	C3	1	1	C3
4B	0	-		0	-		0	-		0	-		0	-	C1	0	-	C3	1	1	C3
5 (PBr29)	0	-		0	-		0	-		0	-		0	-		0	-		1	1	
5A	0	-		0	-		0	-		0	-	C1	0	-	C2	1	-	C3	2	2	C3
5B	0	-		0	-		0	-		0	-	C1	1	1	C2	1	1	C3	3	1	C3
6 (PBk32)	0	-		0	-		0	-		0	-		0	-		0	-		0	-	
6A	0	-		0	-		0	-		0	-		0	-	C1	0	-	C1	2	2	C2
6B	0	-		0	-		0	-		0	-		0	-	C1	0	-	C1	2	2	C2
7 (PBr29)	0	-		0	-		0	-		0	-		0	-		0	-		0	-	
7A	0	-		0	-		0	-		0	-	B1	0	-	B1	0	-	C1/B1	1	1	C2/B1
7B	0	-		0	-		0	-		0	-		0	-		0	-	C1	1	1	C2
8 (PG17)	0	-		0	-		0	-		0	-		0	-		0	-		0	-	
8A	0	-		0	-		0	-		0	-		0	-		0	-		0	-	C1
8B	0	-		0	-		0	-		0	-		0	-		0	-		1	1	C1
9 (PG17)	0	-		0	-		0	-		0	-		0	-		0	-		0	-	
9A	0	-		0	-		0	-		0	-		0	-	C1	0	-	C3	2	1	C3
9B	0	-		0	-		0	-		0	-		0	-	C1	0	-	C3	2	1	C3

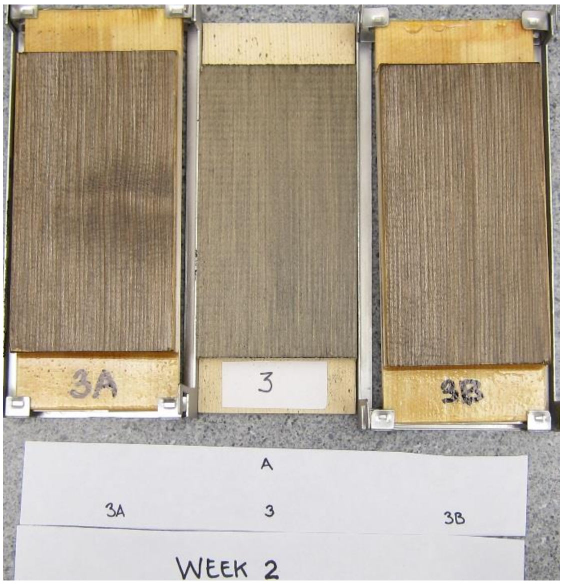
Notes: Y= Yellowing, G= Greying, C=Chalking, B=Bleeding, D=Dirt on a surface, 1= Very slight, 2= Moderate, 3= Severe

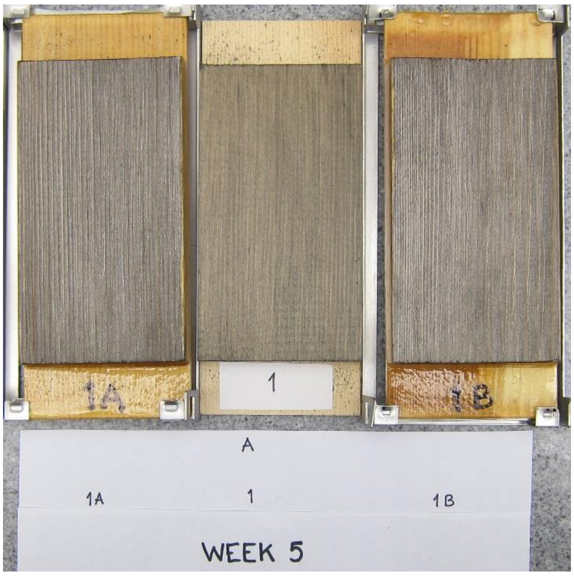
Pictures of accelerated weathering tests (Coating A)

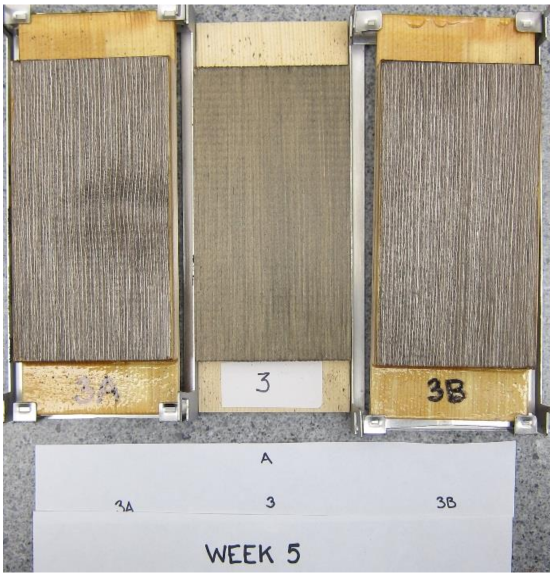
References - PBk7 – PBk11











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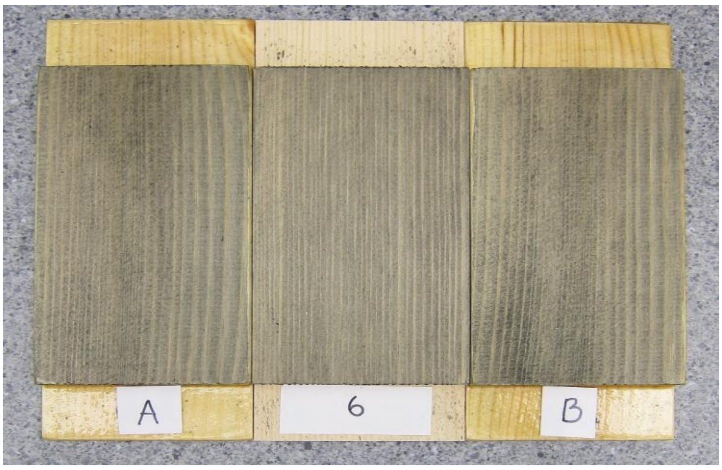
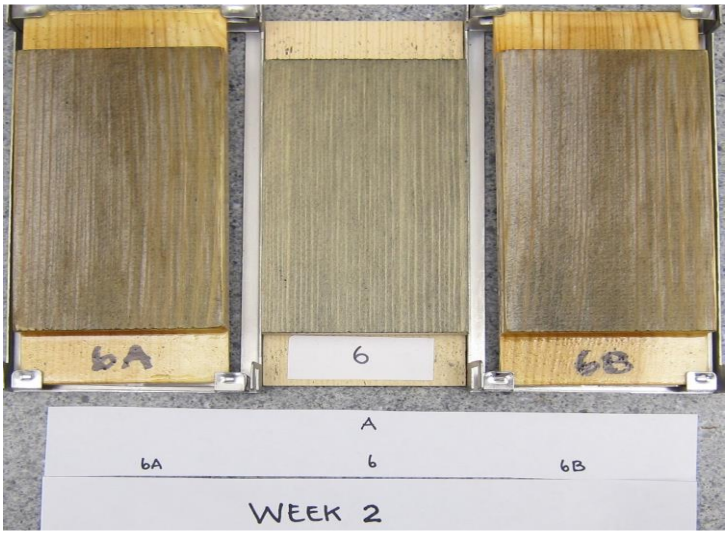
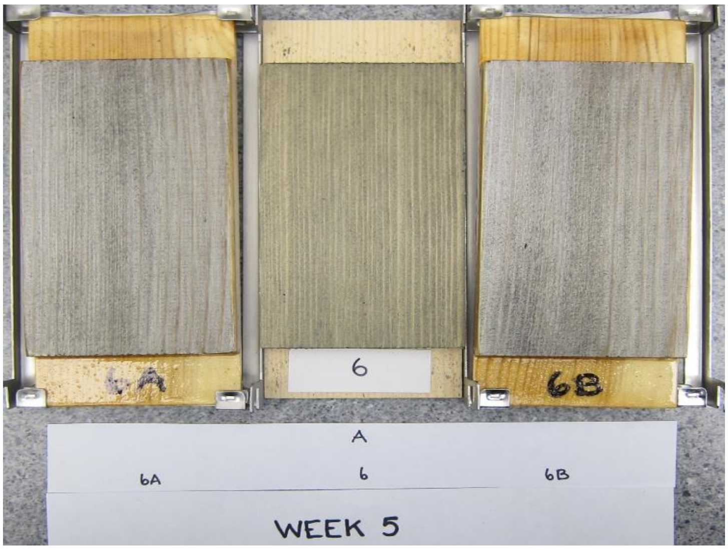
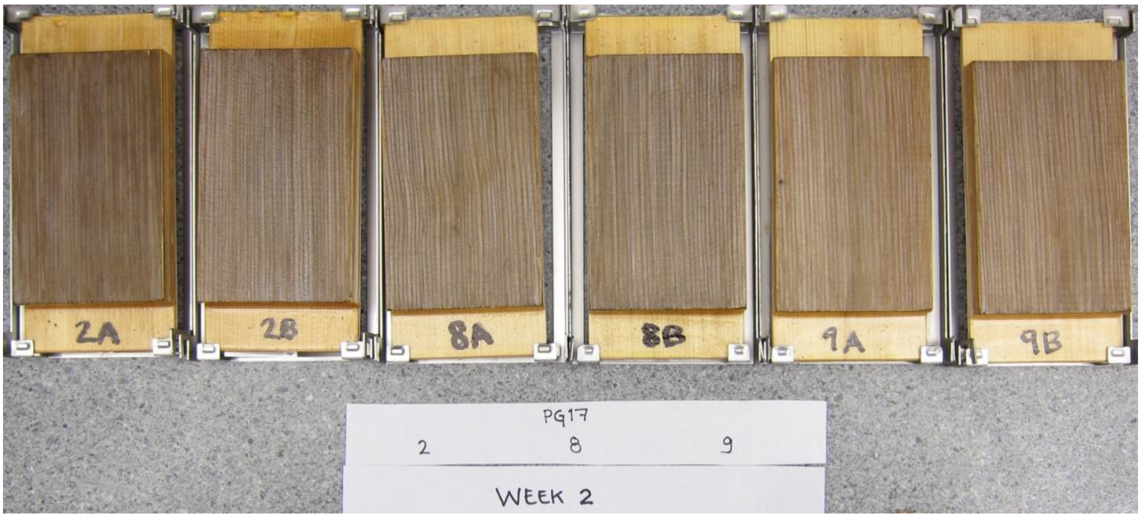






PG17


2A
2B
8A
8B
9A
9B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2B
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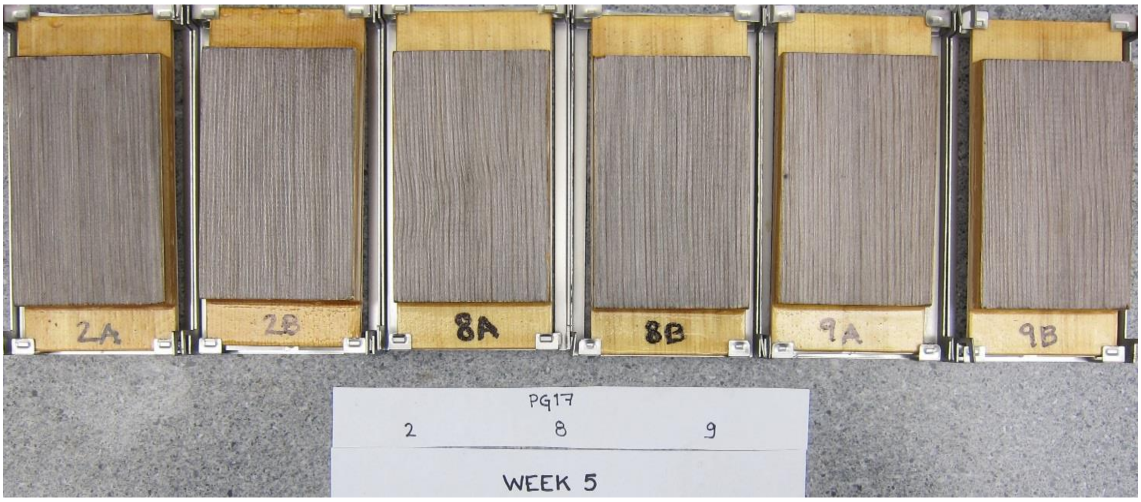
WEEK 2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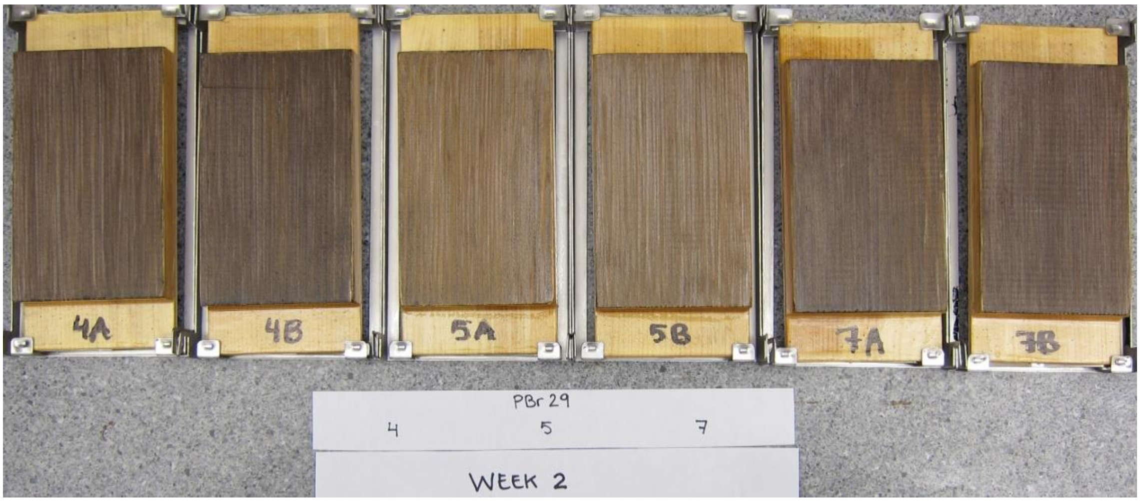
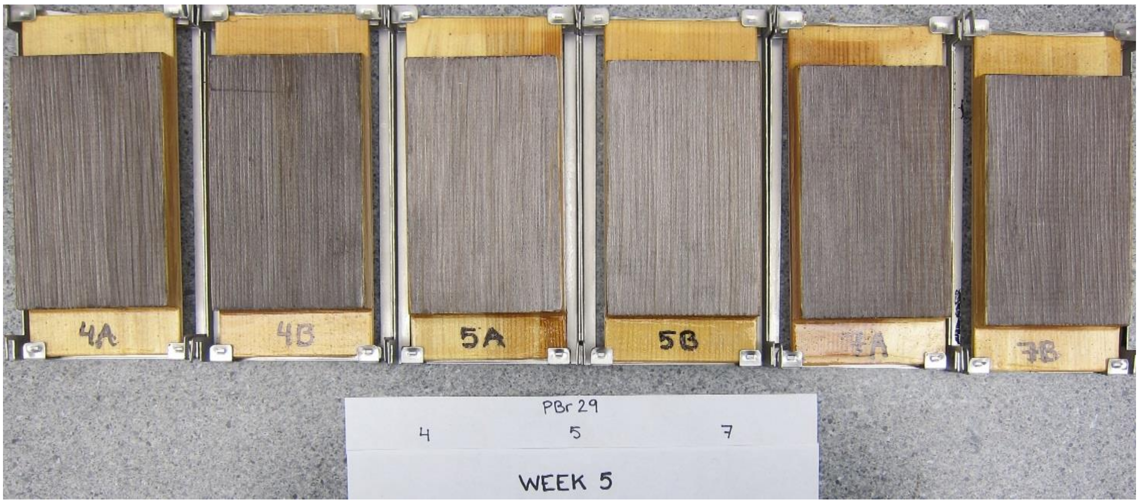
2B
8A
8B
9A
9B
PG17
2
8
9
WEEK 5

PBk29


4A
4B
5A
5B
7A
7B


4A
4B
5A
5B
7A
7B
PBr 29
4
5
7
WEEK 2


4A
4B
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5B
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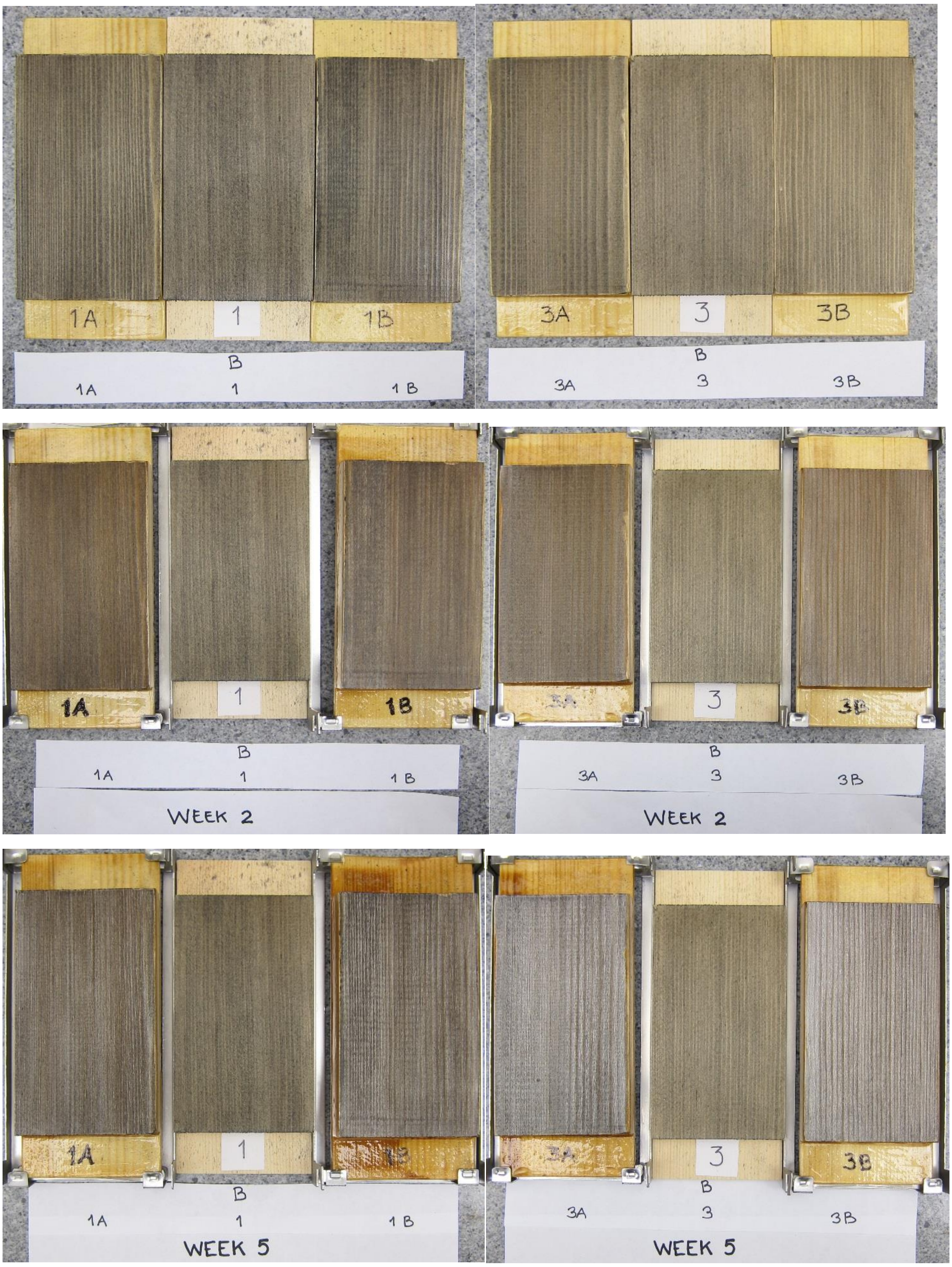
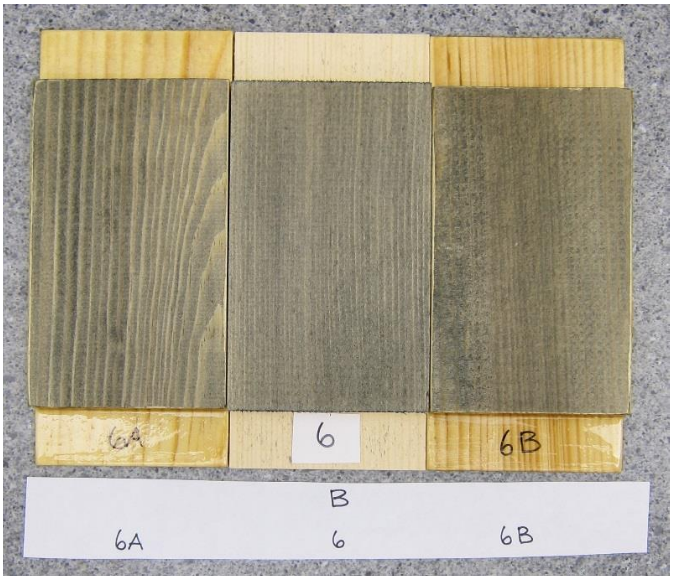
7B
PBr 29
4
5
7
WEEK 5

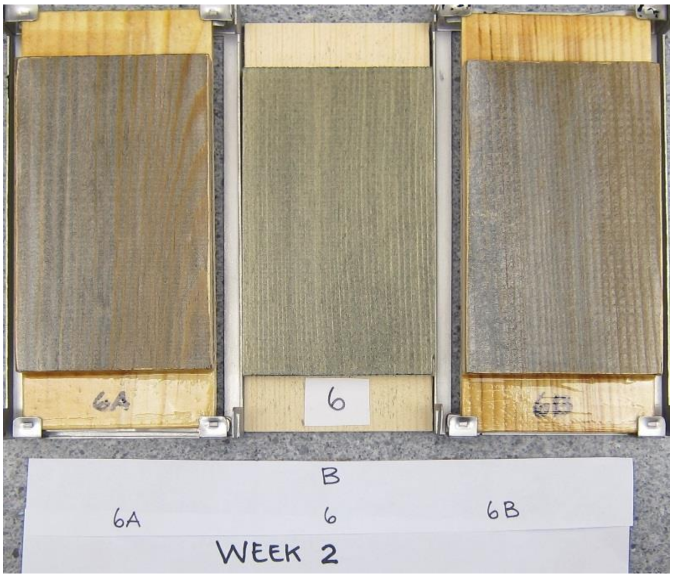
Pictures of accelerated weathering tests (Coating B)

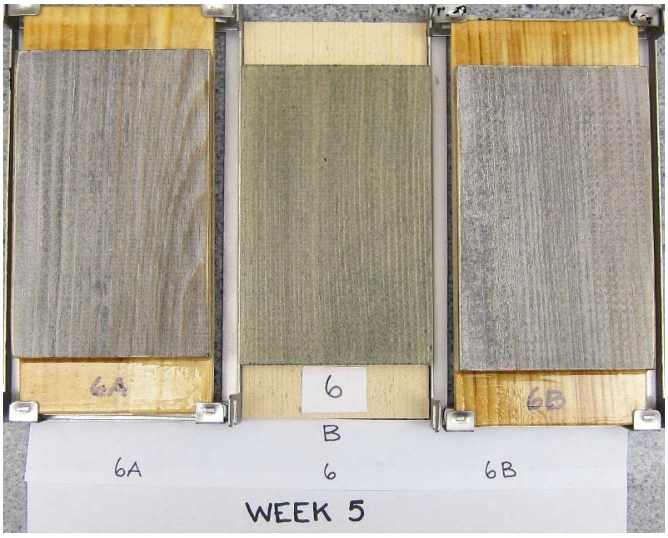
References – PBk7 – PBk11



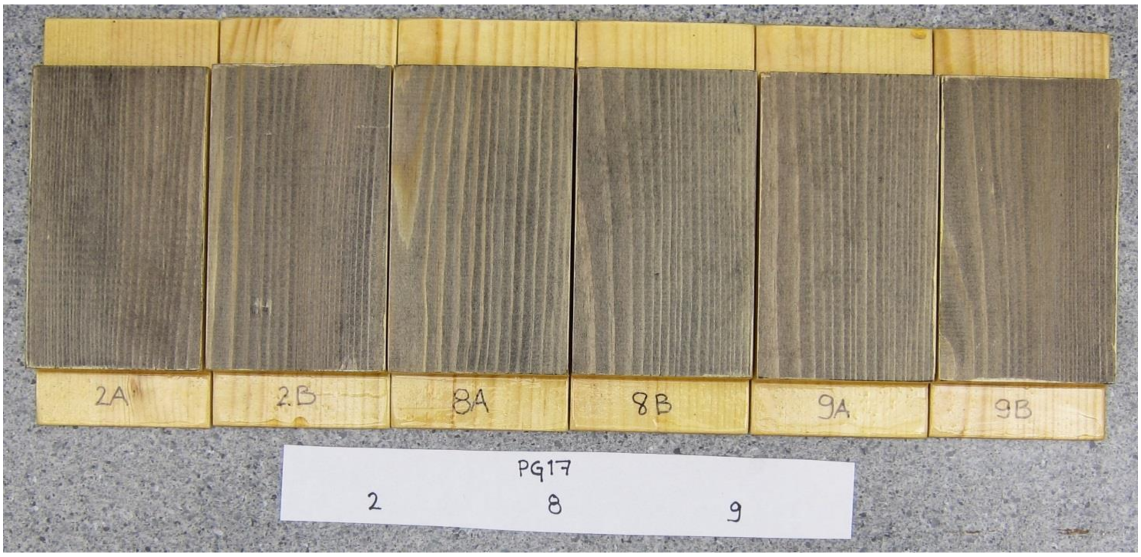
PBk32

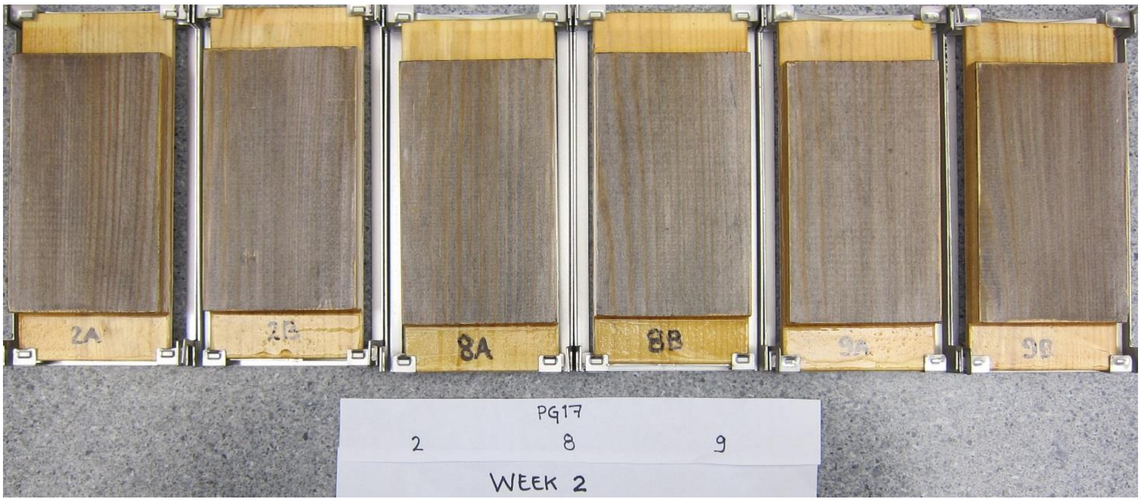






PG17


2A
2B
8A
8B
9A
9B
PG17
2
8
9


2A
2B
8A
8B
9A
9B
PG17
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9
WEEK 2


2A
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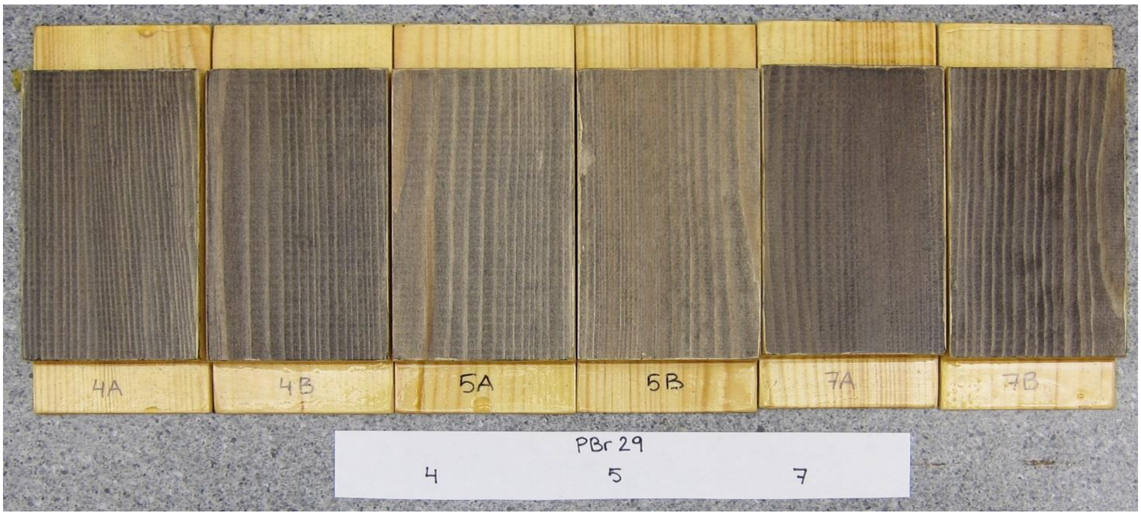
9A
9B
PG17
2
8
9
WEEK 5

PBk29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5B
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7B
PBr 29
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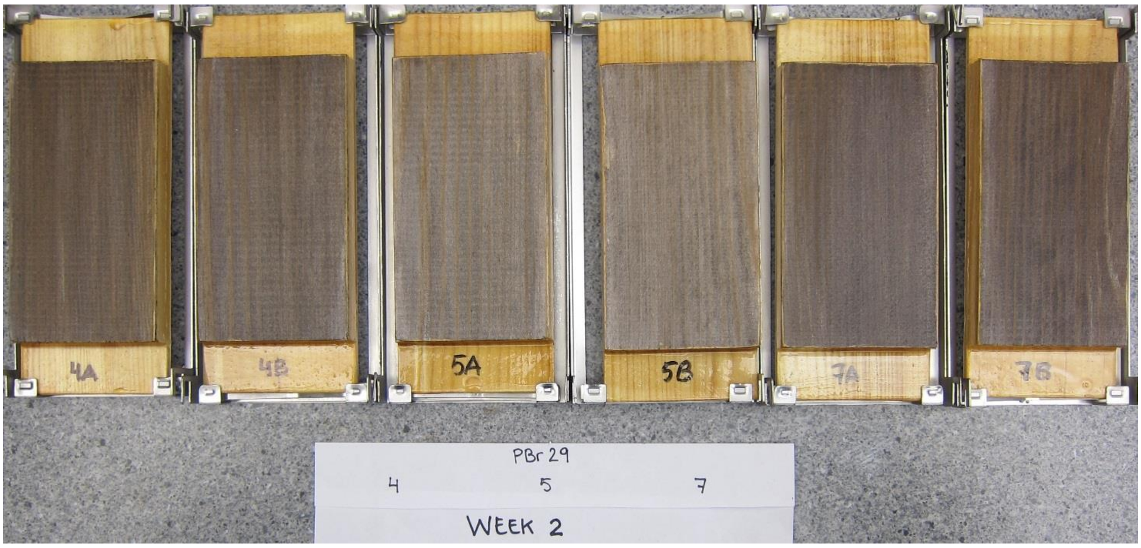
7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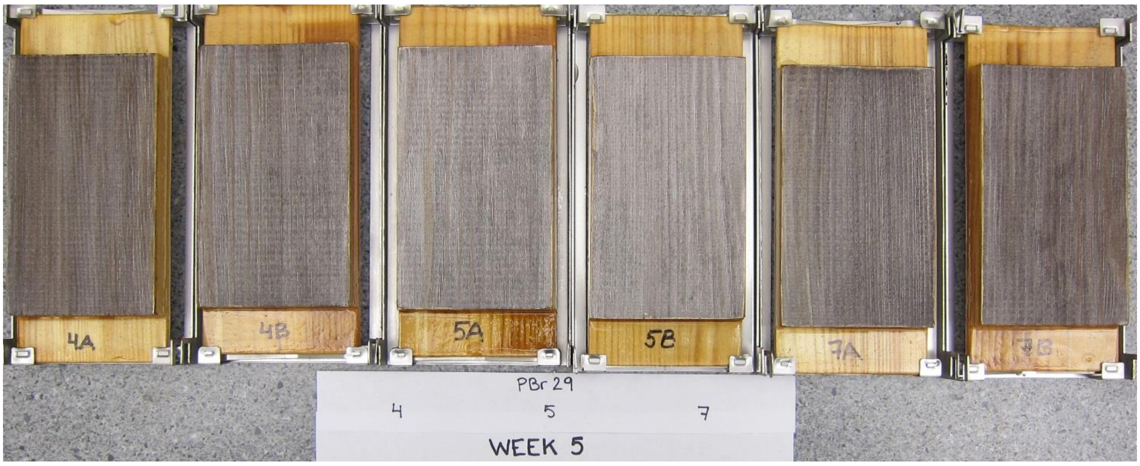
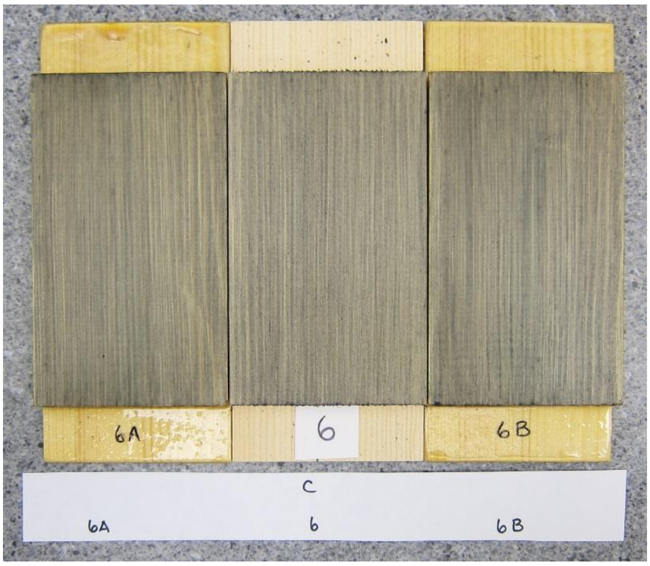
4B
5A
5B
7A
7B
PBr 29
4
5
7
WEEK 2

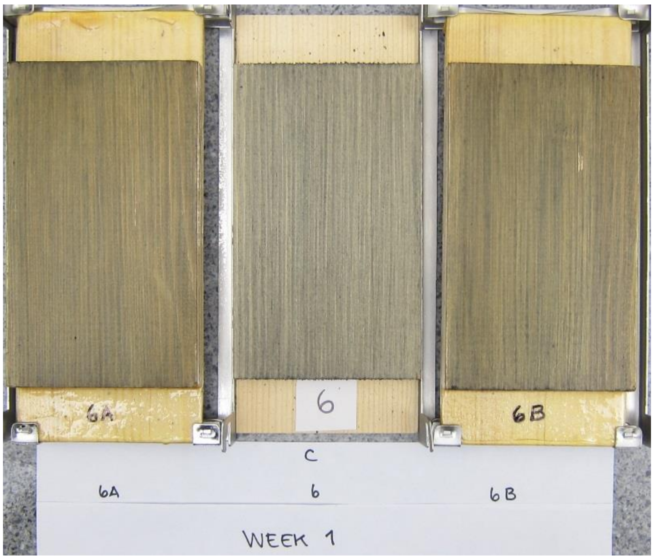

4A
4B
5A
5B
7A
7B
PBr 29
4
5
7
WEEK 5

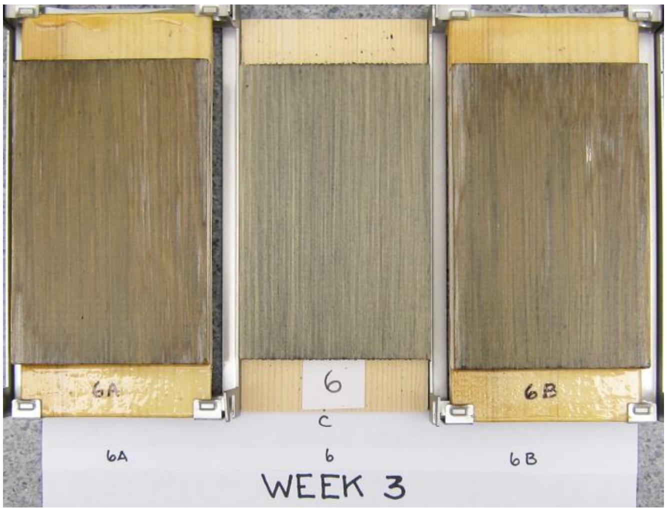
Pictures of accelerated weathering tests (Coating C)

References – PBk7- PBk11

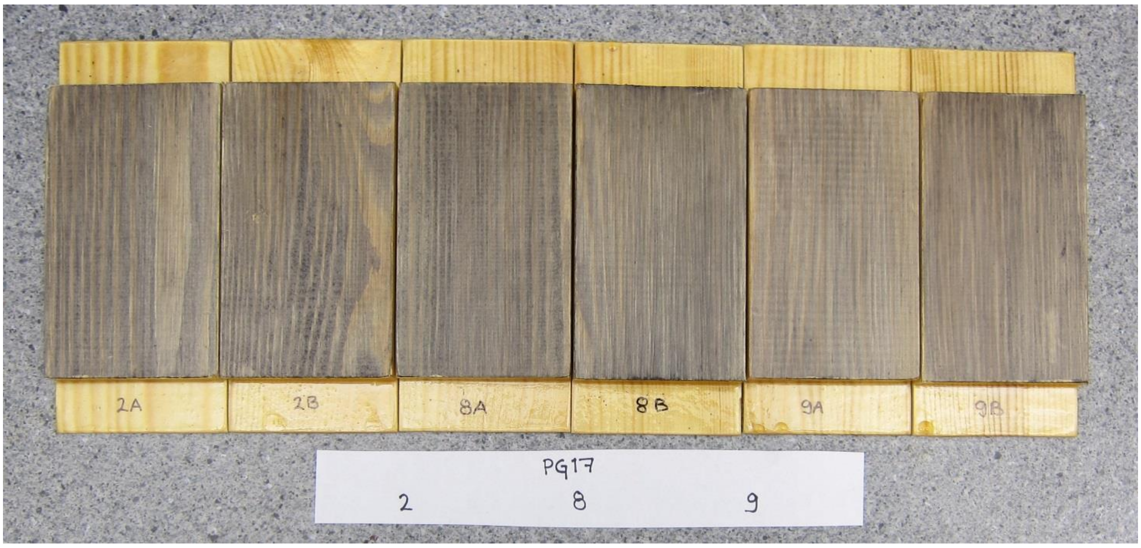
PBk32







PG17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8A
8B
9A
9B
PG17
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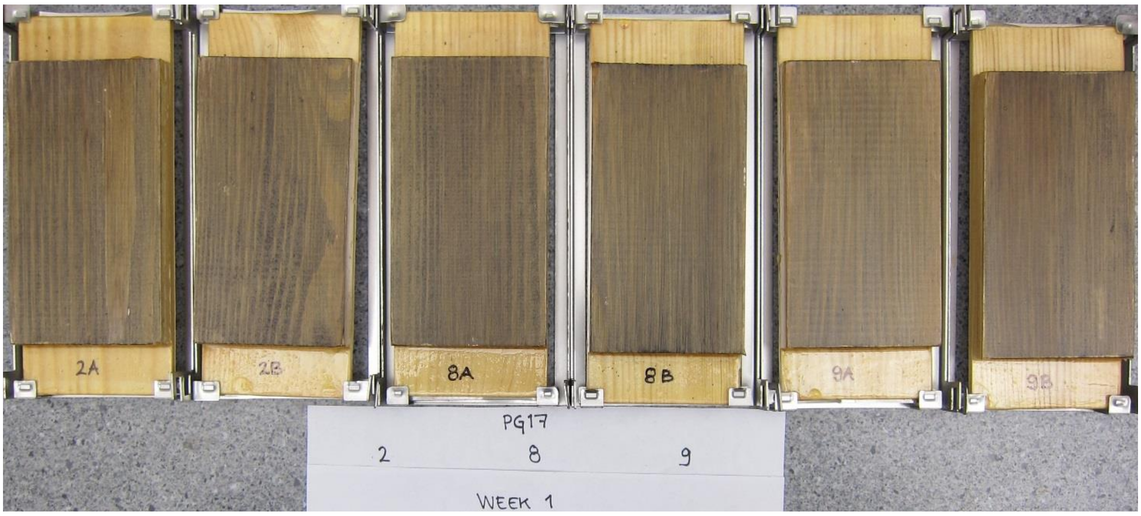
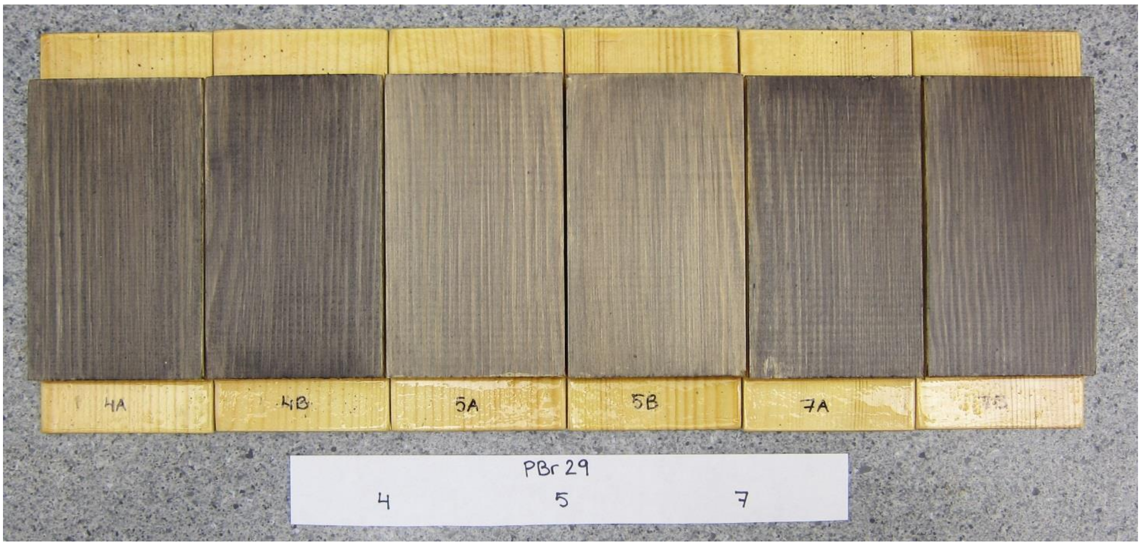
8
9


2A
2B
8A
8B
9A
9B
PG17
2
8
9
WEEK 1


2A
2B
8A
8B
9A
9B
PG17
2
8
9
WEEK 3

PBk29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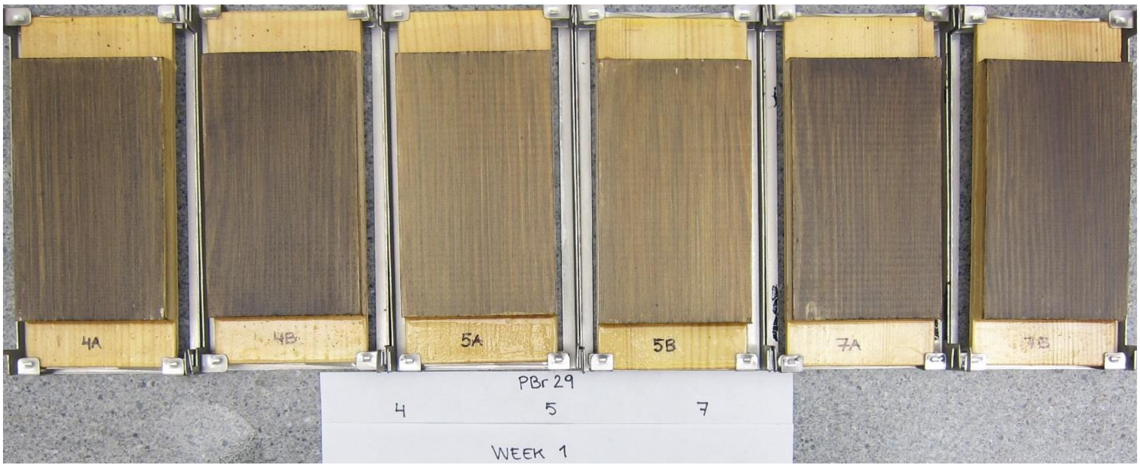
5B
7A
7B
PBr 29
4
5
7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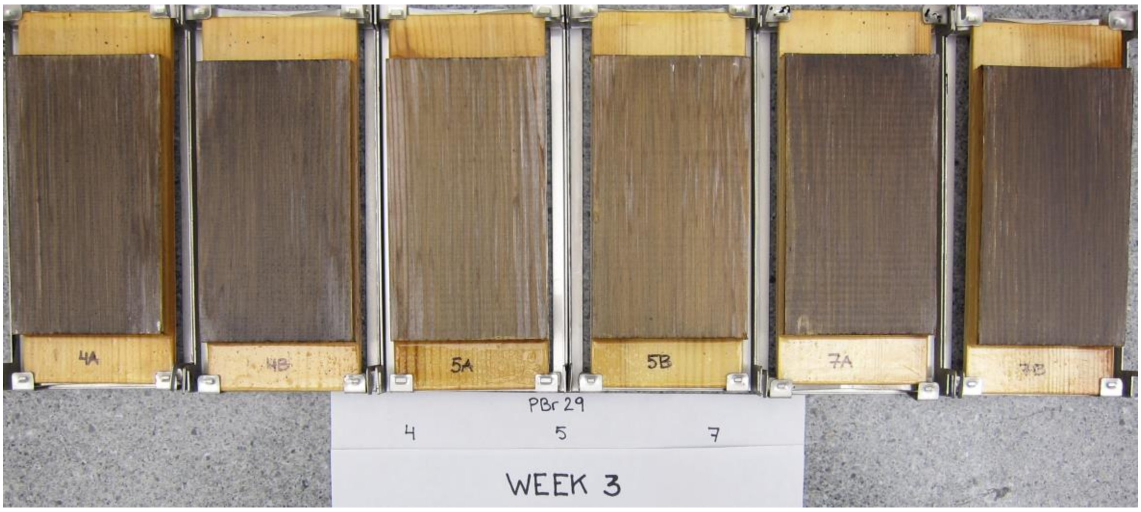
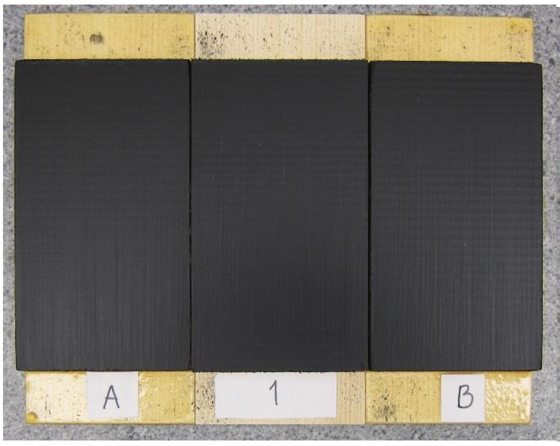
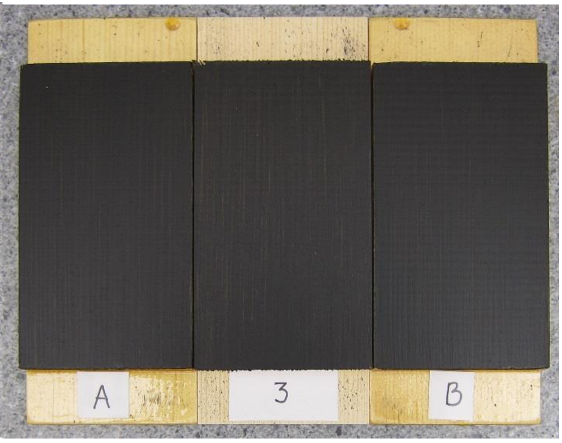
4B
5A
5B
7A
7B
PBr 29
4
5
7
WEEK 1

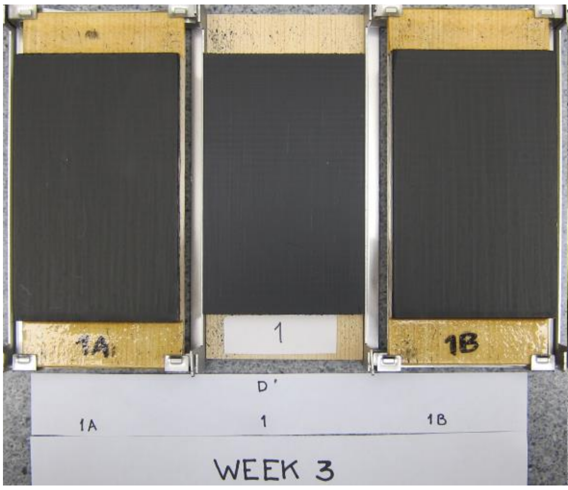

4A
4B
5A
5B
7A
7B
PBr 29
4
5
7
WEEK 3

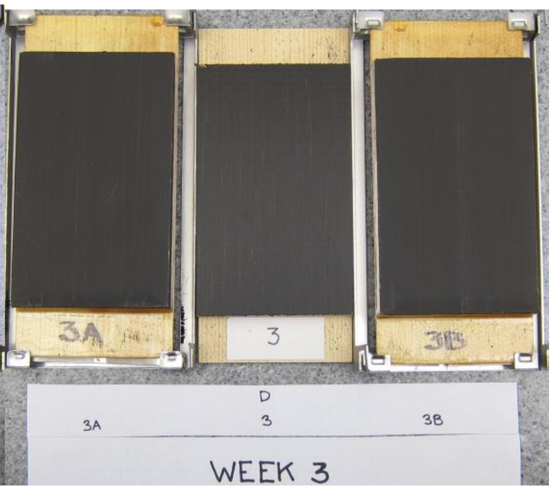
Pictures of accelerated weathering tests (Coating D)

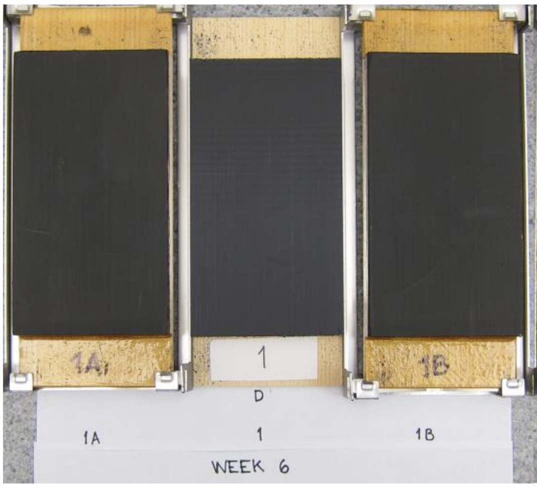
References – PBk7 –PBk11

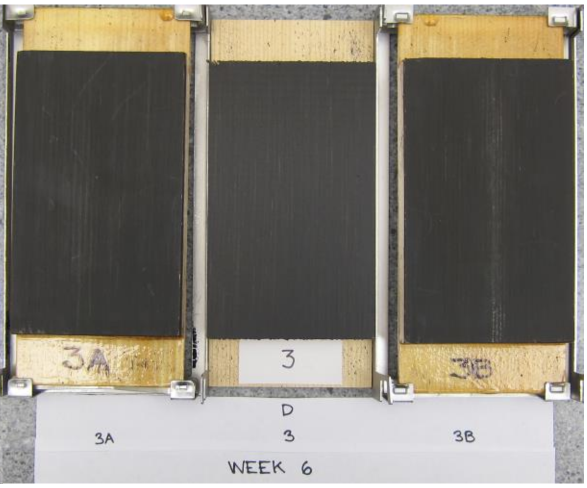




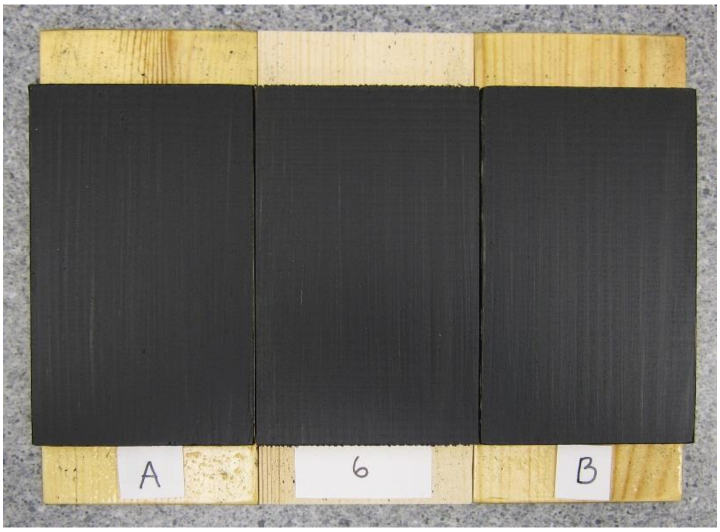


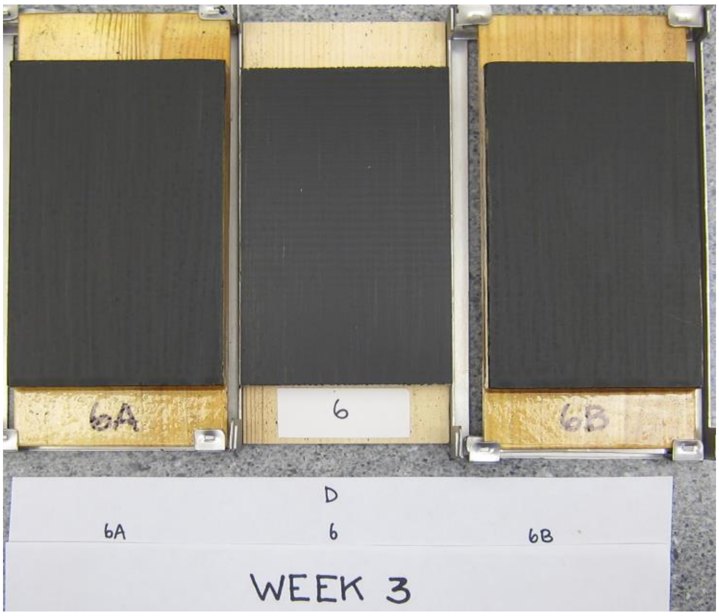


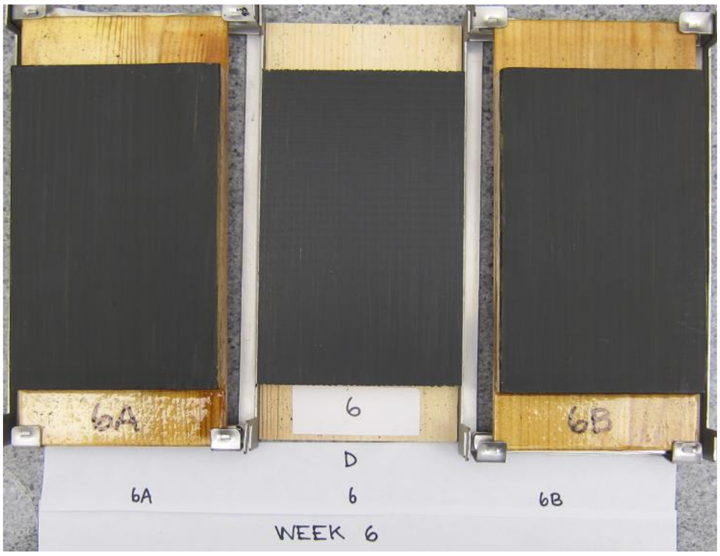




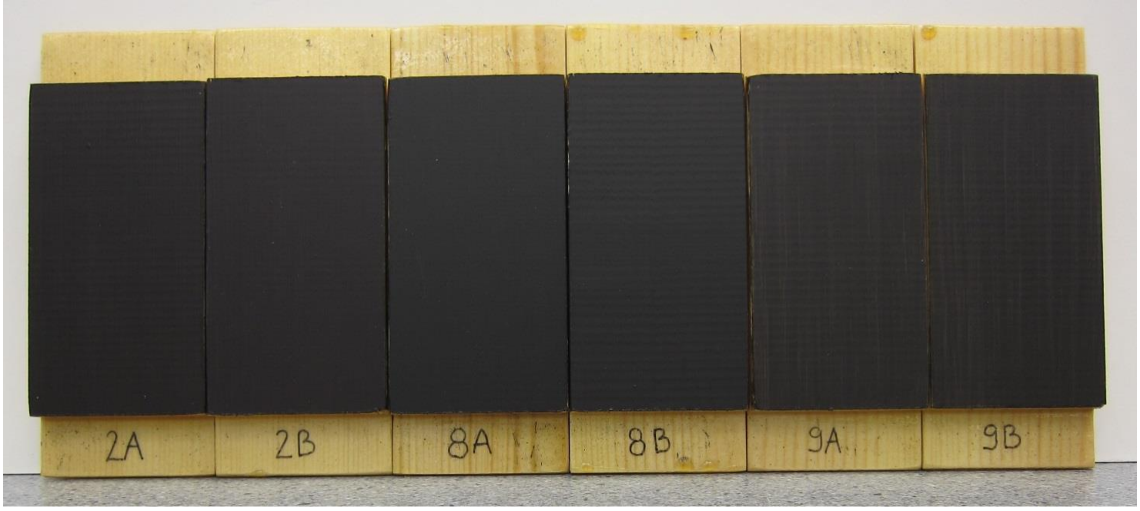
PBk32

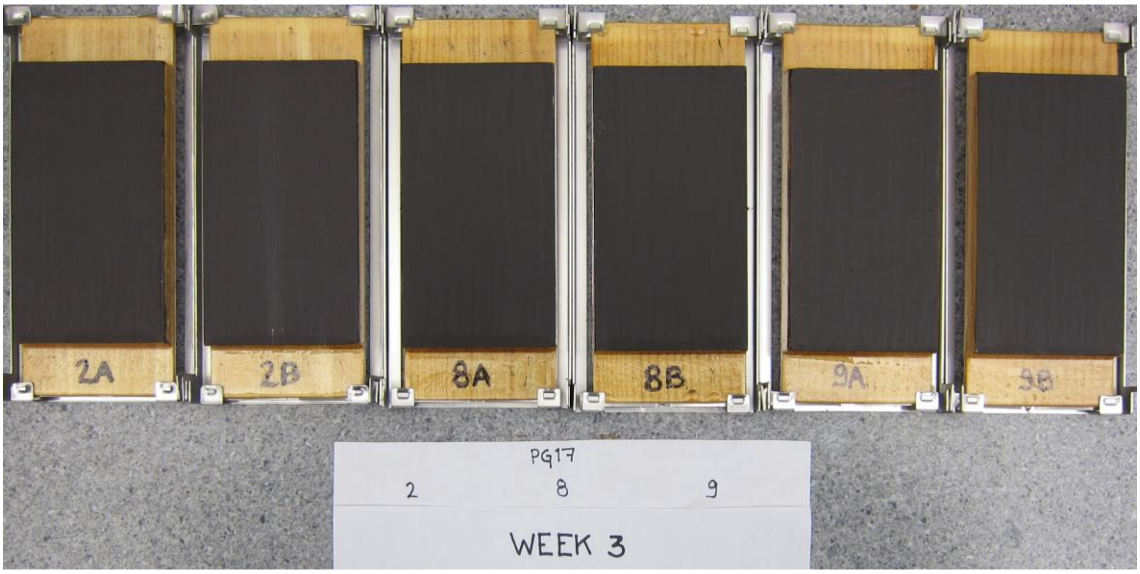


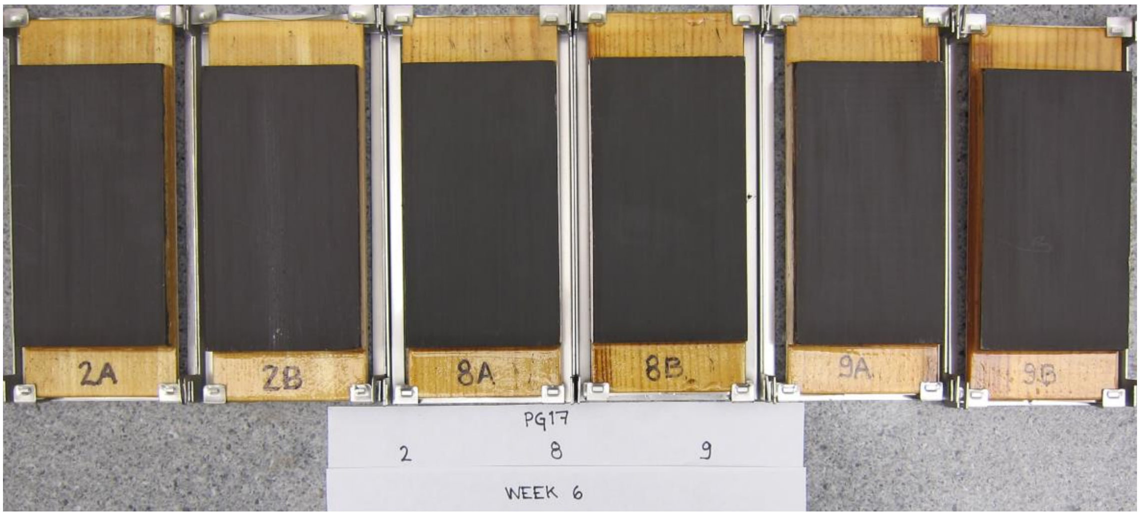




PG17

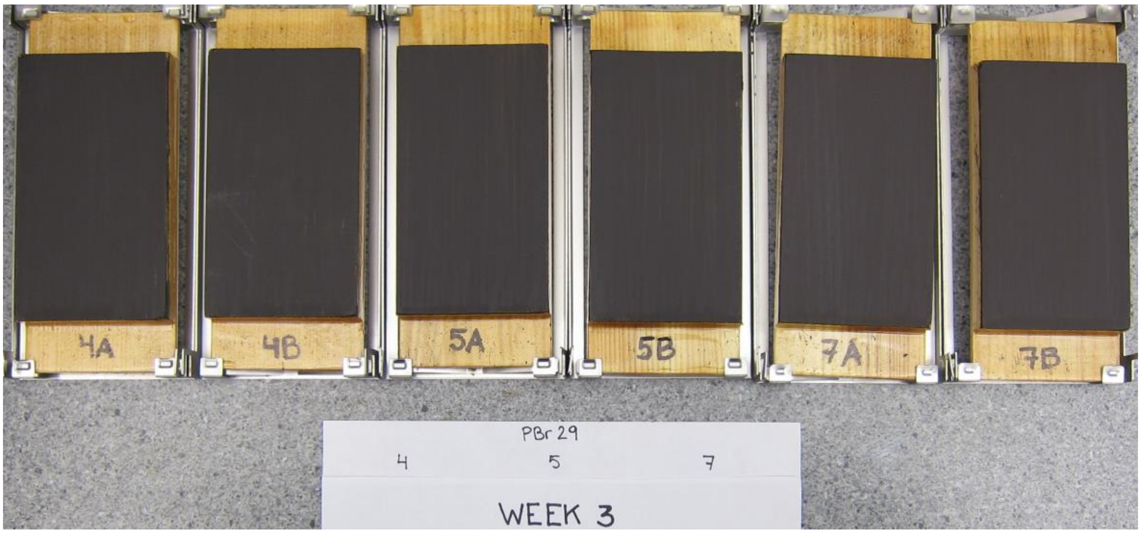

2A
2B
8A
8B
9A
9B

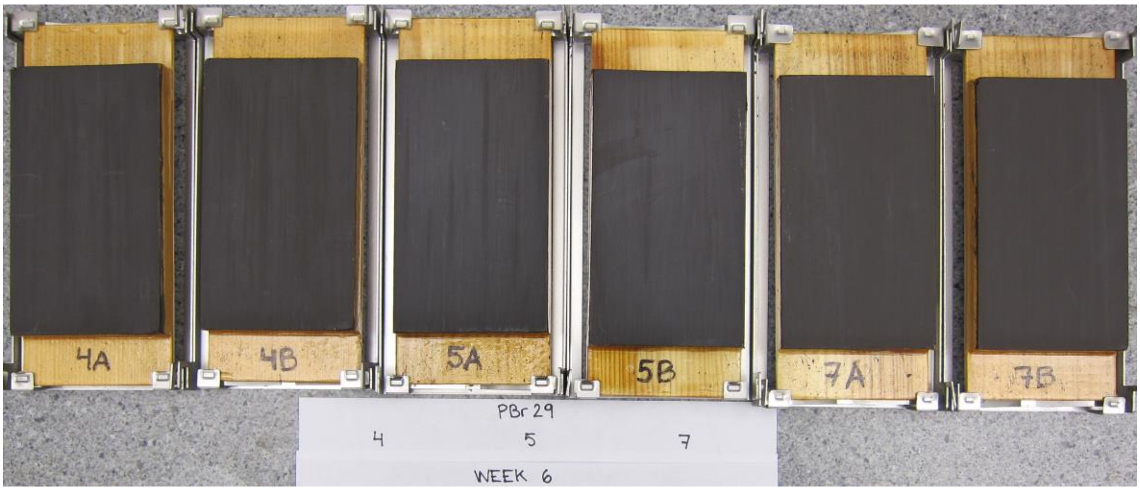

2A
2B
8A
8B
9A
9B
PG17
2
8
9
WEEK 3


2A
2B
8A
8B
9A
9B
PG17
2
8
9
WEEK 6

PBk29


4A
4B
5A
5B
7A
7B


4A
4B
5A
5B
7A
7B
PBr 29
4
5
7
WEEK 3

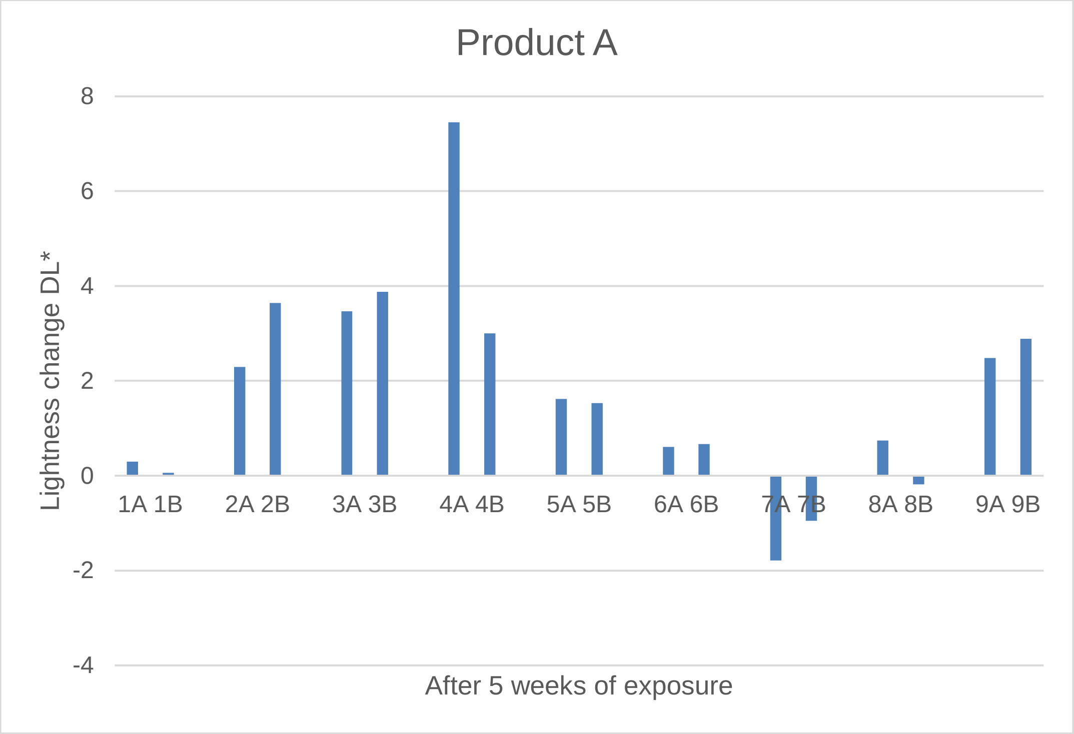

4A
4B
5A
5B
7A
7B
PBr 29
4
5
7
WEEK 6

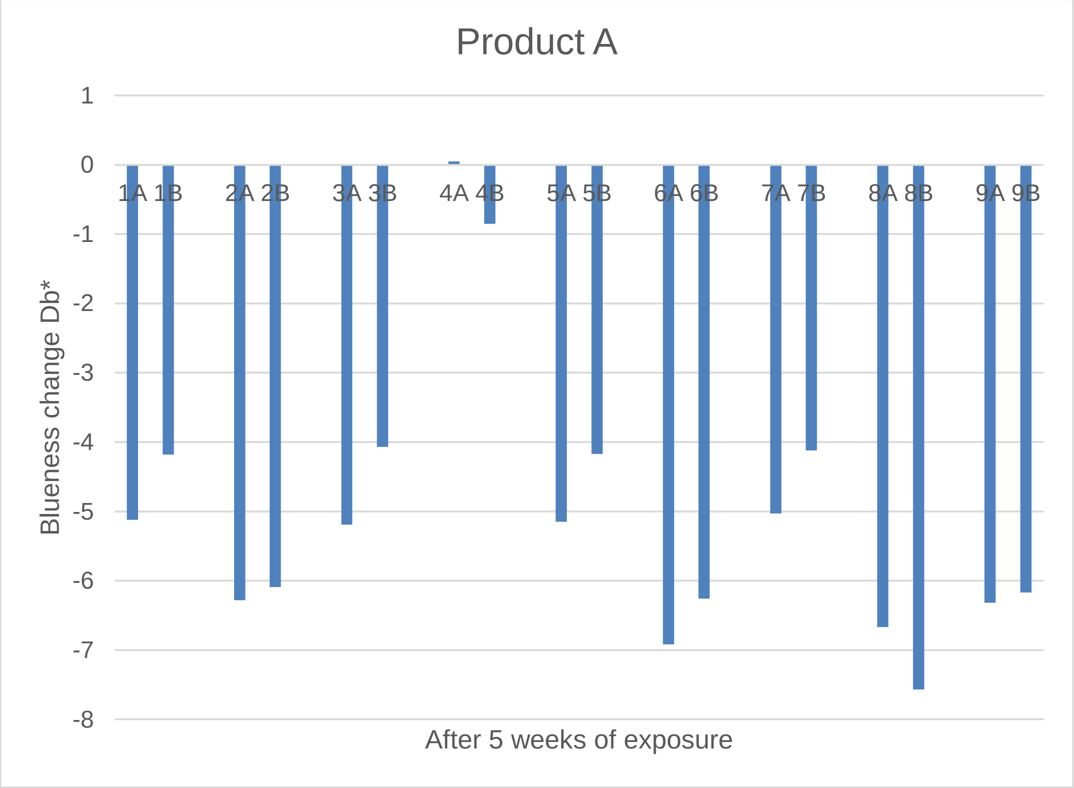
Color measurement results

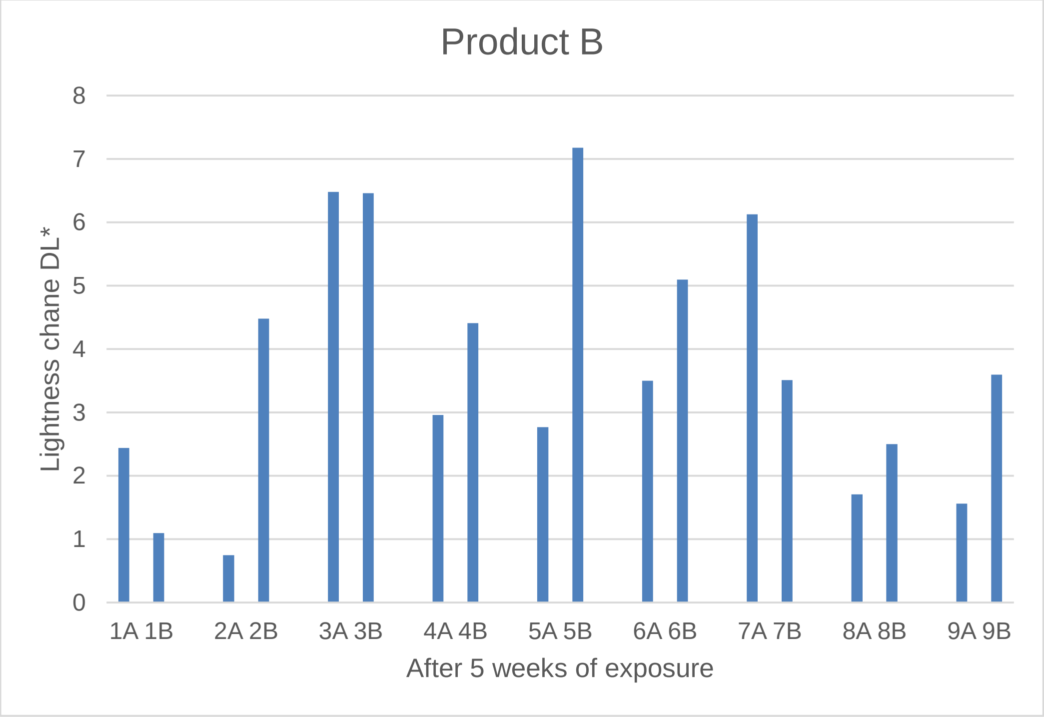
A		DL*	Da*	Db*	B		DL*	Da*	Db*
Standard	1	48,65	3,22	11,09	**Standard**	1	45,07	2,71	9,74
Tolerance +		2,15			**Tolerance +**		2,06		
Tolerance -		2,15			**Tolerance -**		2,06		
	1A	0,3	-0,31	-5,12		1A	2,44	0,86	-0,93
	1B	0,06	0,17	-4,18		1B	1,1	0,43	-2,85
Standard	2	50,53	3,32		**Standard**	2	50,03	3,04	10,68
Tolerance +		2,19			**Tolerance +**		2,18		
Tolerance -		2,19			**Tolerance -**		2,18		
	2A	2,29	-0,18	-6,28		2A	0,75	0,39	-6,38
	2B	3,64	-0,11	-6,09		2B	4,48	-0,33	-7,42
Standard	3	48,04	3,62	12,36	**Standard**	3	49,16	2,89	13,02
Tolerance +		2,13			**Tolerance +**		2,16		
Tolerance -		2,13			**Tolerance -**		2,16		
	3A	3,47	0,38	-5,19		3A	6,48	-0,64	-8,18
	3B	3,88	0,54	-4,07		3B	6,46	0,24	-6,35
Standard	4	40,33	2,22	6,06	**Standard**	4	43,43	2,92	7,86
Tolerance +		1,93			**Tolerance +**		2,01		
Tolerance -		1,93			**Tolerance -**		2,01		
	4A	7,45	1,42	0,05		4A	2,96	0,47	-3,2
	4B	3	1,32	-0,85		4B	4,41	0,21	-3,72
Standard	5	51,01	3,43	10,97	**Standard**	5	51,2	2,96	11,62
Tolerance +		2,2			**Tolerance +**		2,2		
Tolerance -		2,2			**Tolerance -**		2,2		
	5A	1,62	0,16	-5,15		5A	2,77	-0,38	-8,38
	5B	1,53	0,58	-4,17		5B	7,18	-0,5	-8,51
Standard	6	54,75	2,6	12,18	**Standard**	6	50,81	1,89	11,5
Tolerance +		2,28			**Tolerance +**		2,2		
Tolerance -		2,28			**Tolerance -**		2,2		
	6A	0,61	0,31	-6,92		6A	3,5	1,39	-5,75
	6B	0,67	0,52	-6,26		6B	5,1	0,3	-8,43
Standard	7	46,65	3,84	8,6	**Standard**	7	41,44	2,83	7,2
Tolerance +		2,1			**Tolerance +**		1,96		
Tolerance -		2,1			**Tolerance -**		1,96		
	7A	-1,79	-0,14	-5,03		7A	6,13	0,09	-4,06
	7B	-0,95	-0,07	-4,12		7B	3,51	0,89	-2,53
Standard	8	55,01	3,18	11,94	**Standard**	8	51,43	2,24	11,28
Tolerance +		2,29			**Tolerance +**		2,21		
Tolerance -		2,29			**Tolerance -**		2,21		
	8A	0,74	-0,16	-6,67		8A	1,71	0,12	-7,01
	8B	-0,18	-0,34	-7,57		8B	2,5	0,05	-7,54
Standard	9	55,05	3,37	11,59	**Standard**	9	53,65	3,07	12,04
Tolerance +		2,29			**Tolerance +**		2,26		
Tolerance -		2,29			**Tolerance -**		2,26		
	9A	2,48	0,24	-6,32		9A	1,56	-0,24	-7,76
	9B	2,89	0,26	-6,17		9B	3,6	-0,54	-8,67

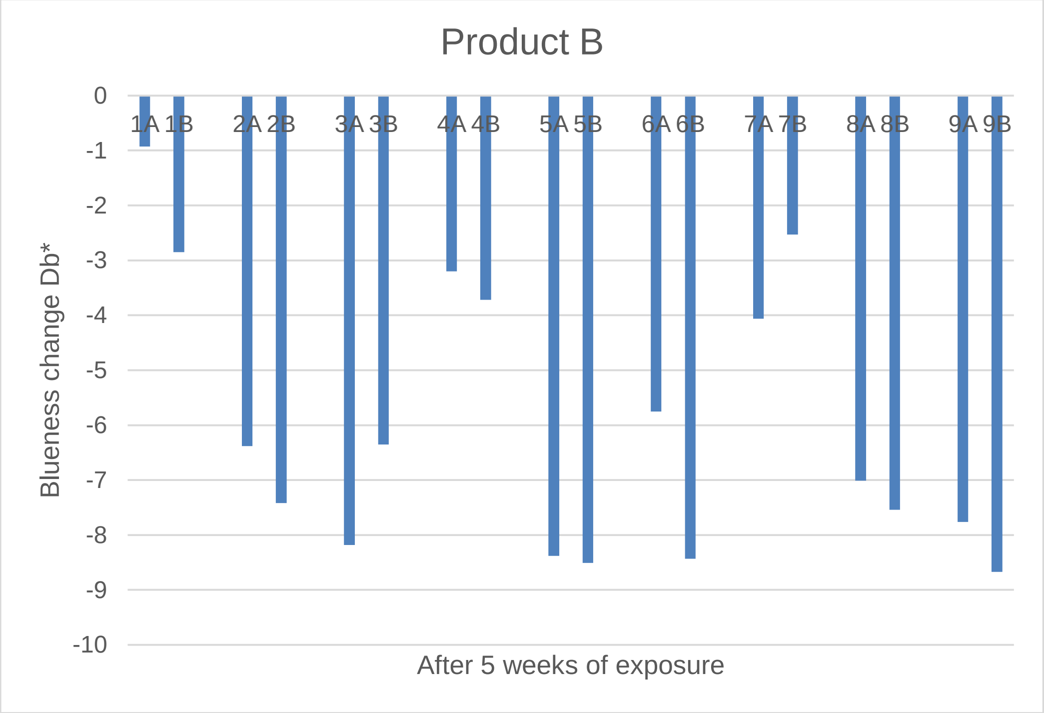
C		DL*	Da*	Db*	D		DL*	Da*	Db*
Standard	1	45,94	3,58	11,06	**Standard**	1	25,53	0,03	-0,52
Tolerance +		2,08			**Tolerance +**		1,44		
Tolerance -		2,08			**Tolerance -**		1,44		
	1A	-8,28	0,99	1,88		1A	1,51	0,36	0,85
	1B	-9,18	0,21	0,2		1B	1,18	0,33	0,76
Standard	2	48,51	3,36	9,05	**Standard**	2	27,26	2,49	0,54
Tolerance +		2,14			**Tolerance +**		1,51		
Tolerance -		2,14			**Tolerance -**		1,51		
	2A	-4,22	2,24	4,96		2A	4,6	-0,51	-0,44
	2B	-6,67	1,49	4,3		2B	4,79	-0,57	-0,47
Standard	3	48,01	3,9	12,17	**Standard**	3	26,99	1,06	1,94
Tolerance +		2,13					1,5		
Tolerance -		2,13					1,5		
	3A	-8,15	2,32	2,75		3A	1,65	-0,04	-0,68
	3B	-7,92	2,34	2,9		3B	1,31	0,11	-0,42
Standard	4	45,22	3,29	7,75	**Standard**	4	27,42	1,82	0,64
Tolerance +		2,06			**Tolerance +**		1,51		
Tolerance -		2,06			**Tolerance -**		1,51		
	4A	-7,27	1,78	2,94		4A	4,57	-0,17	-0,19
	4B	-8,31	1,28	2,04		4B	3,87	-0,1	-0,09
Standard	5	52,07	3,56	11,06	**Standard**	5	26,83	1,85	0,87
Tolerance +		2,22			**Tolerance +**		1,49		
Tolerance -		2,22			**Tolerance -**		1,49		
	5A	-5,6	2,61	5,65		5A	7,3	-0,66	-1,3
	5B	-4,37	3,12	8,04		5B	8,09	-0,62	-1,37
Standard	6	53,2	2,59	10,7	**Standard**	6	25,95	0,16	0,4
Tolerance +		2,25			**Tolerance +**		1,46		
Tolerance -		2,25			**Tolerance -**		1,46		
	6A	-5,4	2,43	8,49		6A	2,84	0,11	-0,42
	6B	-7,06	1,89	7,1		6B	2,78	0,18	-0,41
Standard	7	41,08	3,89	7,02	**Standard**	7	27,49	2,16	0,82
Tolerance +		1,95			**Tolerance +**		1,52		
Tolerance -		1,95			**Tolerance -**		1,52		
	7A	-3,54	1,65	4,28		7A	5,04	-0,47	0,15
	7B	-6,16	1,13	1,47		7B	5,06	-0,39	0,32
Standard	8	51,94	2,97	9,97	**Standard**	8	26,85	1,12	0,41
Tolerance +		2,22			**Tolerance +**		1,49		
Tolerance -		2,22			**Tolerance -**		1,49		
	8A	-10,19	2,04	3,88		8A	3,86	-0,07	0,49
	8B	-8,65	2,1	5,61		8B	3,78	0,17	1,09
Standard	9	52,58	3,73	11,83	**Standard**	9	27,08	1,91	1,28
Tolerance +		2,23			**Tolerance +**		1,5		
Tolerance -		2,23			**Tolerance -**		1,5		
	9A	-6,84	2,22	5,17		9A	4,52	-0,16	-0,9
	9B	-8,57	2,19	4,63		9B	3,95	-0,13	-0,56

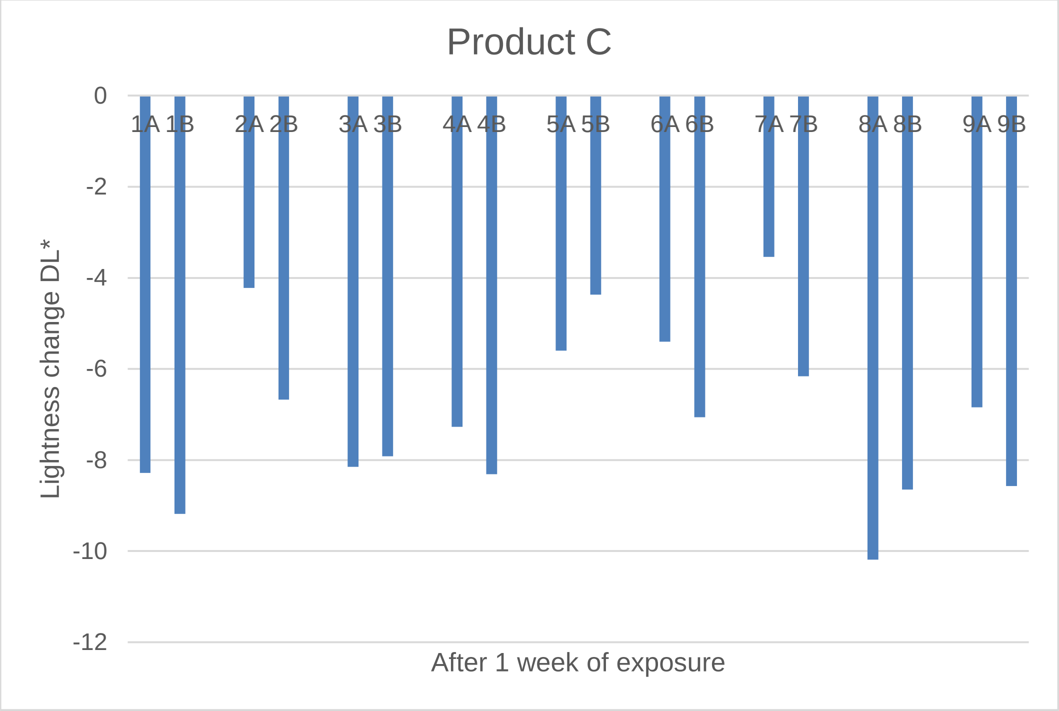
Color measurement graphs






Product B
Lightness chane DL*
8
7
6
5
4
3
2
1
0
1A 1B
2A 2B
3A 3B
4A 4B
5A 5B
6A 6B
7A 7B
8A 8B
9A 9B
After 5 weeks of exposure


Product B
Blueness change Db*
0
-1
-2
-3
-4
-5
-6
-7
-8
-9
-10
1A 1B
2A 2B
3A 3B
4A 4B
5A 5B
6A 6B
7A 7B
8A 8B
9A 9B
After 5 weeks of exposure


Product C
Lightness change DL*
0
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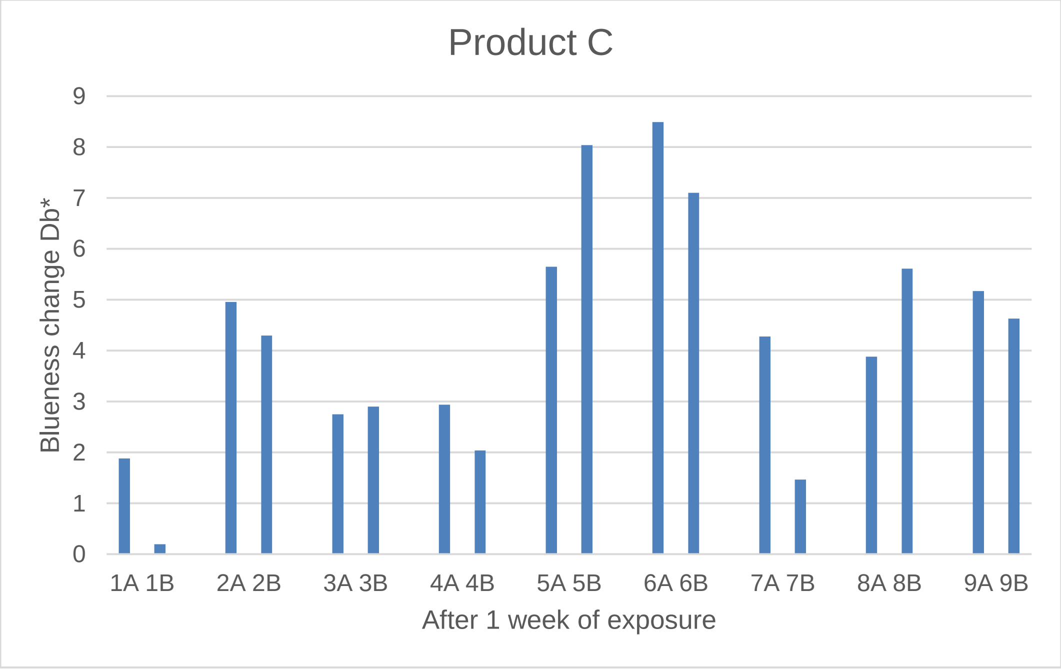
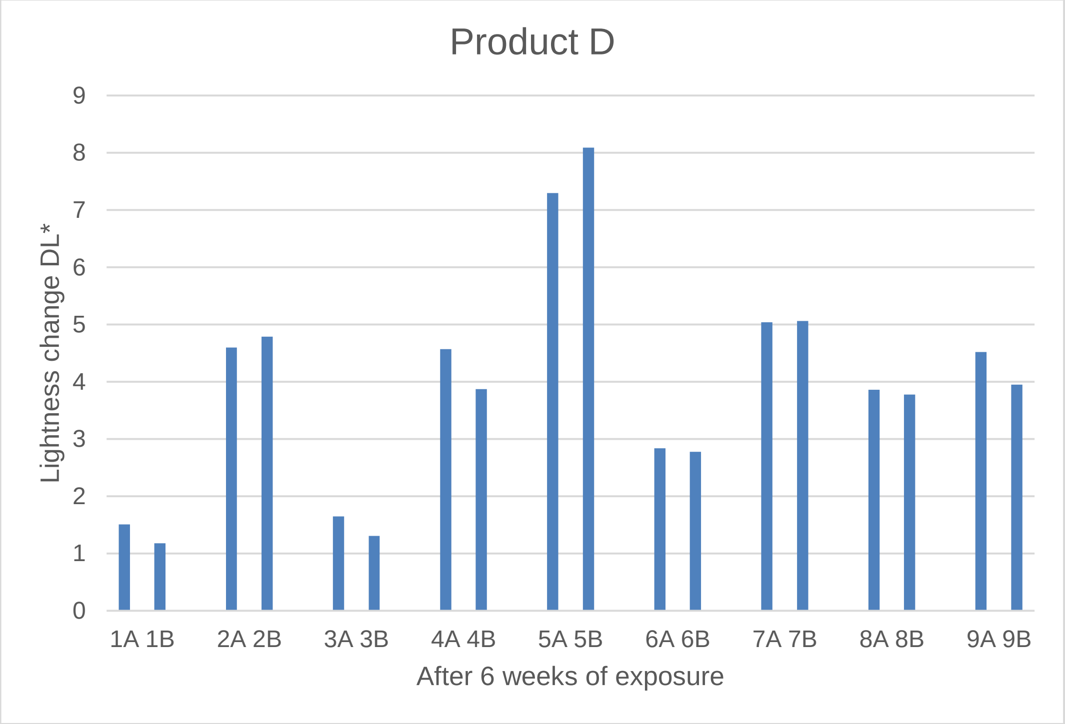
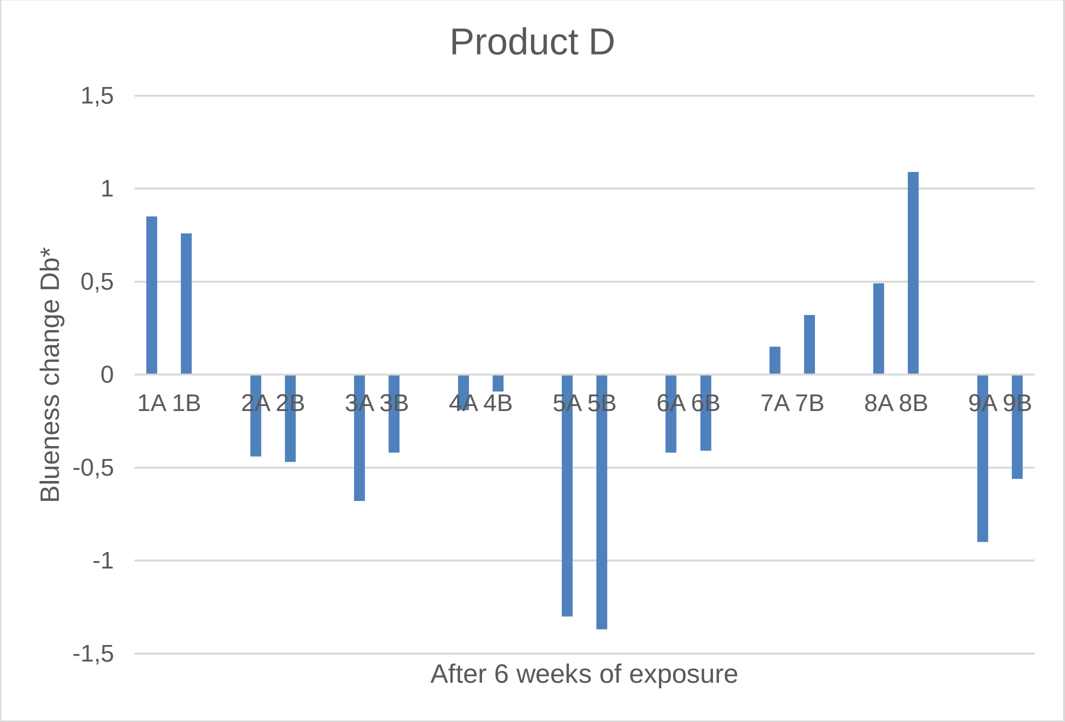
-4
-6
-8
-10
-12
1A 1B
2A 2B
3A 3B
4A 4B
5A 5B
6A 6B
7A 7B
8A 8B
9A 9B
After 1 week of exposure


Product C
Blueness change Db*
9
8
7
6
5
4
3
2
1
0
1A 1B
2A 2B
3A 3B
4A 4B
5A 5B
6A 6B
7A 7B
8A 8B
9A 9B
After 1 week of exposure


Product D
Lightness change DL*
9
8
7
6
5
4
3
2
1
0
1A 1B
2A 2B
3A 3B
4A 4B
5A 5B
6A 6B
7A 7B
8A 8B
9A 9B
After 6 weeks of exposure


Product D
Blueness change Db*
1,5
1
0,5
0
-0,5
-1
-1,5
1A 1B
2A 2B
3A 3B
4A 4B
5A 5B
6A 6B
7A 7B
8A 8B
9A 9B
After 6 weeks of exposure