TALLINNA TEHNIKAÜLIKOOL
TALLINN UNIVERSITY OF TECHNOLOGY

Department of Materials and Environmental Technology

NATURAL WEATHERING OF BIO-BASED FACADE MATERIALS

PUIDUPÕHISTE FASSAADIMATERJALIDE VASTUPIDAVUS VÄLISKESKKONNAS

MASTER THESIS

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AUTHOR’S DECLARATION

Hereby I declare, that I have written this thesis independently.

No academic degree has been applied for based on this material. All works, major viewpoints and data of the other authors used in this thesis have been referenced.

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THESIS TASK

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Study programme:Technology of Wood and Plastic (KVEM)

Main speciality: Wood Technology

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Thesis topic:

(in English) Natural Weathering of Bio-Based Facade Materials

(in Estonian) Puidupõhiste fassaadimaterjalide vastupidavus väliskeskkonnas

Thesis main objectives:

1.Long-term weathering of bio-based facade materials

2. Colour change of bio-based facade materials

3. Surface checking of bio-based facade materials

Thesis tasks and time schedule:

No	Task description	Deadline
1.	Selection of topic	7.03.2017
2.	Start of experiments	14.03.2017
3.	Colour measurements	Every month for first 6 weeks, every 4 weeks for first 6 months, after that every 6 months
4.	Check Measurements	Every 3 months
5.	Photos taken	First six weeks every week, later every month
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8.	Master thesis ready	29.05.2019

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PREFACE

120 bio-based facade materials are being tested in outdoor conditions. Tests are contributing to the BIO4ever project that has a goal of "fulfilling gaps of lacking knowledge on some fundamental properties of novel bio-based building materials". BIO4ever is an international project that has a practical outcome in a simulation software that visualizes the appearance change of facade materials.

Author of this thesis contributes to the project by evaluating colour change and surface checking of bio-based materials in an Estonian climate. The aim of this master thesis is to evaluate weathering resistance of 120 bio-based materials in an Estonian climate. Materials under evaluation have been gathered from over 30 companies locating in 17 different countries. Weathering tests in Estonia are carried out in TalTech Laboratory of Wood Technology weathering site. (59°23'50.6"N 24°39'24.0"E). Materials are exposed in a 45˚ inclination stand to southern direction. Materials weathered in a 45˚ angle degrade almost twice as fast as materials weathered vertically. Facades are mainly used vertically, therefore, it could be also referred to these tests as "natural accelerated weathering".

2-year weathering tests indicated that natural and impregnated materials have a bad colour stability while surface, chemical and hybrid modification mainly improved the colour stability of materials. Thermally modified materials had moderate colour stability. Natural, thermally modified and impregnated materials had the longest and widest surface checks. Surface modified and composite materials were the best for improving resistance of materials against surface checking. Chemically modified materials were moderately prone to surface checking.

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Keywords: BIO4ever, Natural Weathering, Bio-Based Materials, Wood, Colour, Checks.

INTRODUCTION

The world has understood that it is not possible to keep exploiting non-renewable resources as this kind of approach is not sustainable. Therefore, there is an increasing need for bio-based renewable alternatives (i.e. wood) to make our living environment more sustainable. Construction sector is one of the areas where wood could be used more instead of non-renewable materials.

One of the reasons why bio-based materials are not used to their full potential, is the lack of confidence in the operational durability of those materials. BIO4ever project wants to solve the issue and raise awareness about benefits of using bio-based materials in a construction sector. BIO4ever is an international project and author of the thesis is contributing to the project by measuring weathering resistance of bio-based materials in an Estonian climate. Practical outcome of the BIO4ever project is a software that simulates the appearance change of bio-based facade materials. Therefore, confidence about using bio-based materials will improve as the appearance change of bio-based facade materials will become more predictable.

The aim of this master thesis is to evaluate weathering resistance of 120 bio-based materials in an Estonian climate. Weathering resistance of bio-based facade materials will be evaluated by the colour change and appearance of checks. Experiments are taking place in TalTech Laboratory of Wood Technology outdoor weathering test site (59°23'50.6"N 24°39'24.0"E), where materials are exposed to natural weather conditions on a weathering stand. The stand is in a 45˚ inclination which means that experiments could also be considered as natural accelerated weathering for facade materials as facades are mostly vertical and weathering in a 45˚ angle degrades materials approximately two times faster than in a vertical weathering. The stand is faced to a southern direction so that materials would be maximally exposed to weather conditions. Materials are weathered for 2 years.

The Master Thesis is divided largely into 4 chapters. First chapter introduces the BIO4ever project. Second chapter is a literature overview about wood in outdoor conditions. Third chapter presents materials that are used in tests and explains how the experiments were conducted. Fourth chapter is for results and analysis to make conclusions about results gathered during experiments.

1 BIO4EVER PROJECT

In Today´s world, too many non-renewable materials are being used and this is not sustainable. Problem has been noticed by politicians also as European politics for upcoming years are to reduce environmental impact of the building sector (Petrillo *et al*, 2018a). Therefore, direct renewable alternatives are needed for the applications of non-renewable materials (Hill, 2006).

Forest resources form approximately 30% of the Earth´s land area but wood covers only 1,6% of the most used construction materials in Europe. This shows that wood is not used up to its potential and there is a large market share to be gabbed from other materials. (Hill, 2006; Herzceg *et al*, 2014)

One of the main factors why wood has not been used as much as it could have been, is its limited operational durability (Sandak *et al*, 2017a). However, new innovative wood protection methods have been developed that are improving wood properties. Therefore, confidence about using wood as a construction material needs to be raised by demonstrating benefits of using bio-based materials as a construction / facade material (Petrillo *et al*, 2018a).

That is what BIO4ever project is doing, demonstrating benefits of using bio-based materials as a facade material. "The overall goal of the BIO4ever project is to contribute to public awareness, by demonstrating the environmental benefits to be gained from the knowledge-based use of bio-based materials in buildings facades" (Sandak *et al*, 2018a).

In the BIO4ever project, 120 materials that were gathered from all over the world are being tested. Over 30 industrial and academic partners from 17 countries have contributed by sending their specimens. Most participants are from Europe, but Costa Rica and New Zealand companies have contributed to the project, as well (Sandak *et al*, 2018a). Samples include various natural wood species, composite panels, thermally modified, chemically modified, impregnated, surface treated, and hybrid treated bio-based materials. (Sandak *et al*, 2018c)

Multi-sensory approach is used to evaluate weathering impact on the materials. Leading working group of this project in Italy evaluated materials by colour, gloss, roughness, wettability for appearance changes and by measurements from spectroscopy in VIS, NIR and IR ranges for chemical changes. Each month, photos are taken to capture the appearance change (Sandak *et al*, 2018a). In addition, resistance of specimens against insects was investigated, as well (Sandak *et al*, 2018d).

The most important outcomes of this project are accurate service life prediction, cost of the service life and aesthetical performance models of bio-based building materials (Sandak *et al*, 2018c). Bio-based building materials are lacking trustworthy models for describing their performance during service life, therefore, a software simulating the performance of bio-based facade materials will be developed (Sandak *et al*, 2016a). Software is based on variables such as appearance change of the materials, weather dose map and specific layout of the building. If data of these 3 variables are put together then a 3D model visualization can be done. Photos taken during weathering tests are used for the interactive simulation of facades appearance. (Sandak *et al*, 2018a)

Software that will be developed from the gathered data will enable visualization of the building facade appearance by selecting facade material, building location and duration of the exposure. Changing geographical location of the building will adjust how selected material will change its appearance during time. Based on the location of the building a proper maintenance schedule will be recommended by the software, ensuring the realistic aesthetical expectations of the user (Petrillo *et al*, 2018a). Illustration about what this software is going to do can be seen in Figure 1.1. This particular Figure illustrates how building facade constructed from Norway Spruce (*Picea Abies*) has changed its appearance after 12 months of weathering. This is only an illustration as the final software tends to be more realistic. (Sandak *et al*, 2018a)

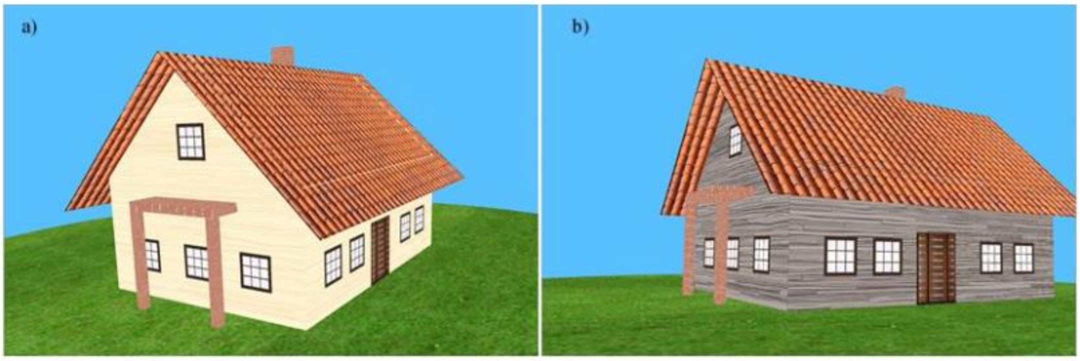

Figure 1.1. Visualization of building facade appearance after 12 months of natural weathering (Sandak *et al*, 2018a)

Developed software is meant for wide range of users such as investors, architects, construction engineers, professional builders, suppliers, final customers, etc. (Sandak *et al*, 2018a)

2 WOOD IN OUTDOOR CONDITIONS

Wood is a biomaterial that has a huge potential regarding the demand for renewable building materials. However, there are various factors that are making it challenging to use wood in construction applications. For example, weathering is one of the main factors that is causing the appearance change of wood when exposed to outdoor conditions. Fortunately, many protection treatments have been developed to improve weathering resistance of a wooden material. Following chapters will describe the influence of weathering, methods to evaluate appearance changes and protection of wood in outdoor conditions.

2.1 Weathering

Weathering is a process where materials are slowly degrading due their exposure to weather factors (Sandak *et al*, 2016b). It is one of the most efficient degradation processes as it affects strongly aesthetics of a material and makes it challenging to protect materials from it. Change of aesthetics is especially tragic for facades as an important goal of the facade, besides physical protection and hygro-thermal balance, is to give an aesthetically good look to a building. Deterioration of the facade surface while weathering is unavoidable, but this problem can be minimized by proper maintenance or replacements (Sandak *et al*, 2018c).

In case of weathering, materials are changing their properties because of various factors (Figure 2.1). These factors include solar radiation (UV, visible, infrared and other spectra), water, atmospheric temperature, humidity, oxygen (and other atmospheric gases), wind, dust, micro-organisms, etc (Reinprecht, 2016). These factors can change the appearance of a material strongly as they usually act in synergy (Rowell, 2013). Weathering affects materials mainly by changing their colour, gloss, roughness and creating environment for checks and mould to appear (Sandak A. & Sandak J., 2017; Bucur, 2011).

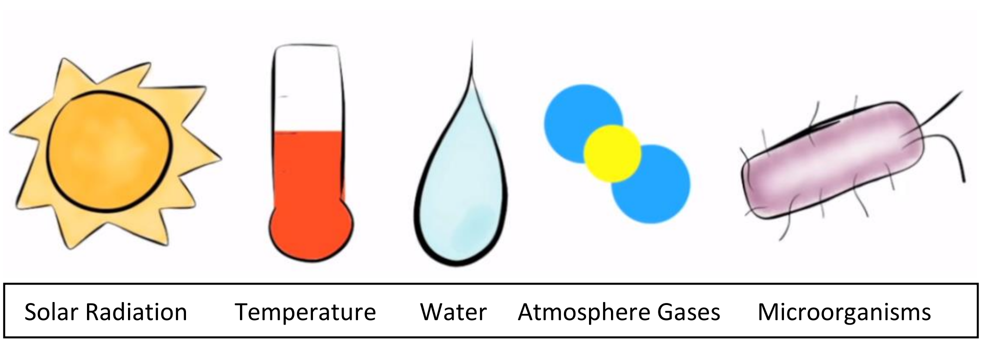

Figure 2.1. Wood degrading factors during weathering (Drollinger, 2013)

Wood consists mainly from cellulose, hemicellulose and lignin. Lignin can be easily affected by UV radiation. Photo-degradation of the wood begins when it is exopsed to the sunlight (Bucur, 2011). UV radiation radicalises lignin particles, therefore enabling it to react with oxygen (Rowell, 2013). Rainwater and wind are "washing out" the photo-degraded particles of lignin and other extractives, therefore causing changes in structural composition and aesthetics of the wood. This process illustrates perfectly how different weather factors are harming wood in collaboration. (Mohebby & Saei, 2015)

Wood gets its colour mainly from extractives. Without extractives wood is greyish. Visible light is strong enough to degrade extractives but with UV radiation this process is much faster as UV radiation is more effective (Bucur, 2011; Rowell, 2013). Wood loses its original colour only from the surface as UV radiation cannot access the inner parts of the wood (Oberhofnerova *et al,* 2017). This means that original colour can be restored by proper maintenance methods (i.e. sanding). Weathered natural biomaterials will turn into greyish colour (Figure 2.2) within the first few months of exposure (Sandak *et al*, 2017b).

Figure 2.2. Weathered wooden facade (Lindman, 2014)

Temperature individually is unlikely to degrade wood as atmospheric temperature is unable to heat up wood to so high degrees that it would start degrading (Rowell, 2013). However, temperature accelerates photo-oxidation process as research work of Persze and Tolvaj (2011) confirmed the accelerating impact of temperature in photo-oxidation process. They stated that temperature is influencing how much wood is affected by the sunlight. When wood is exposed to sunlight in higher temperatures then wood changes its colour more rapidly than wood exposed to sunlight in lower temperatures (Persze and Tolvaj, 2011).

Another method how weathering is affecting wood is the appearance of checks on the wood surface (Figure 2.3). The reason why checks are appearing on the wood is mainly because of moisture that causes internal drying stresses when drying. Checks will appear when wood moisture content is below 30% and moisture leaves wood inconsistently. Uneven or fast drying causes tensions and microdefects in wood are torn apart and increasing (Saarman & Veibri, 2005; Bucur 2011).

Figure 2.3. Checks on the weathered wood surface (GORI, 2017)

Weathering can happen with a different speed. The rate of weathering is affected by wood species, finishing type, technical design and climate conditions. Weathering of the materials depends largely on the exposure direction as south direction is considered the most degrading direction because it is exposed to the UV radiation the most (Sandak *et al*, 2018c). Study of Dimitriou *et al* (2017) showed that during their weathering experiments at different locations, the highest colour change occurred in Turkey while lowest in UK (Dimitriou *et al*, 2017). Difference was caused by the intensity of weathering as materials in Turkey got more sunlight. Therefore, UV radiation has a major role in changing appearance of the materials and as southern direction exposes materials to the sun the most, it is the most degrading exposure direction for materials.

In addition to previously named factors, rate of weathering is influenced by the inclination angle of exposure, as well. Evans (1996) made an experiment were 3 different exposure angles were used for wood weathering: 0˚C (horizontal), 45˚C and 90˚C (vertical). Most rapid degradation happened for specimens that were exposed in a horizontal angle and slowest degradation was in a vertical angle. Difference between 0˚C and 45˚C angle of exposure was not remarkable as wood exposed in those degrees degraded rapidly, wood in a horizontal angle degraded only slightly faster. However, difference between vertical stand and other exposure angles was significant as vertically exposed wood degraded almost twice as slow as wood exposed in other angles. Therefore, 0˚ and 45˚ angle weahtering could be considered as a natural accelerated weathering of facade materials as facades are mostly vertical.

Surface of the weathered wood is quite often colonized by microorganisms but usually weathering is not favouring decay as intermittent wetting and drying of the wood is not favorable for decaying fungi to appear. Thus, weathering has minimal impact on mechanical strength of the timber. Confirmation of this can be found in Norway where wooden churches have been exposed for weathering over 1000 years but they are still mechanically strong. (Rowell, 2013)

When decay problems for above ground materials appear then they are usually caused by bad design or construction. Wood components in buildings should be protected from the rain and from trapping of the rainwater. If conditions are so that wood can not be held dry then wood should be protected with preservatives. (Forest Products Laboratory, 2010)

When materials are in outdoor conditions, it is possible that unpredictable factors (i.e. vandalism, fire, storms) can harm appearance of the materials, as well. This problem should be considered while doing experiments or designing constructions in outdoor conditions. (Sandak A. & Sandak J., 2017)

2.2 Methods for Evaluating Appearance Changes

Appearance of the wood can be evaluated with several methods such as visual, sensoric, microscopic etc. Preferred methods for measuring materials are non-destructive methods because it allows monitoring of the materials as experiments can continue after measurements are taken (Sandak A. & Sandak J., 2017). The most basic sensing techniques for evaluation of surface aesthetics of weathered materials are shown in Table 2.1.

Table 2.1. Techniques for surface aesthetics evalutation (Sandak A. & Sandak J., 2017)

Sensor	**Human Senses**	**Colour Meter**	**Gloss Meter**	**Roughness Meter**
Example				

Human senses are the simplest method to assess aesthetics of materials but downside of this method is its subjectivity (Sandak *et al*, 2017b). For a visual evaluation, it is possible to picture or scan materials with a photo camera / scanner to be able to compare the appearance change of materials in time. Nevertheless, visual evaluation remains very subjective. There are many scales invented for visual assessment of the wood surface. One example that was used by De Windt *et al* (2014) is shown in Table 2.2. (De Windt *et al*, 2014)

Table 2.2. Visual evaluation scale (De Windt *et al*, 2014)

Rating	Degradation	Characteristics
0	None	No changes
2	Small changes	Colour / gloss changes
4	Small changes with mild	Coating layer slightly damaged, blue stain less than 10% of the area
6	Moderate changes	Limited erosion, thin checks, blue stain 10 - 30%
8	Large changes	Flaking less than 50% of the surface area, checking of the wood surface, blue stain 50 - 75% of the area
10	Enormous changes	Flaking more than 50% of the surface area, major checking, blue stain 75% or more of the surface area

Rating 0 is given to materials that have not changed their original aesthetics. Rating 2 is for materials that have colour or gloss changes but beside that are looking good. Rating 4 is given to materials that have some kind of damage in the coating layer and where some sort of blue stain can be spotted. Rating 6 is given when erosion can be spotted, small checks are on the surface and blue stain covers materials until 1/3 of the surface area. Rating 8 means that flaking can be spotted, surface of the material is checking and blue stain covers approximately 50 – 75% of the surface area. Rating 10 is the largest and is given to materials that have flaking over 50%, major cracking of the surface and blue stain fungi covers over 75% of the surface area. Still, visual assessment is very subjective and that is why sensoric approach is more preferred. (De Windt *et al*, 2014)

Study of Dimitriou *et al* (2017) also pointed out that for human eye the most important factor affecting the human perception of wood degradation state is the colour. Other factors like roughness and glossiness did not have as big impact on human perception. Therefore, assessment by human senses is largely subjective and focusing mainly on the colour change. (Dimitriou *et al*, 2017).

Different sensors are mirroring and converting human senses into language of numbers. That way it can be more precisely and objectively describe the situation of materials. Optics and electronics have developed so far that it is possible to take measurements in an experimental site. Colour, gloss and roughness meters were shown in Table 2.1. They are one of the most common methods to measure aesthetics of the wood surface. They give reliable data and are relatively easy to use, that´s why they are often used. It is suggested to use multi-sensor approach as using only one sensor method would not give as complete results. (Rowell, 2013)

Another factor that influences appearance of wood is surface checking. Checks on a wood surface can be detected visually or automatically. Visually can be measured such parameters as check length, width, depth and quantity. Checks can be measured with mechanical measurement tools such as rulers, calipers, micrometres and feeler gauges (Christy *et al*, 2005). Manual methods for measuring checks are very laborious. Therefore, different automatic methods have been used for measurements. More modern check detection methods are, for example, reflection of laser and fluorescent light. They are non-destructive methods, therefore enabling experiments to continue after measurements are taken. (Bucur, 2011)

Additional methods that give overview about chemical and microscopic properties are spectroscopic and microscopic methods. Spectroscopic methods can be divided into three different classes: molecular, electronic and mass spectroscopies. Molecular spectroscopies are, for example, Fourier Transform Infrared (FTIR) and Fourier Transform Attenuated Total Reflectance Infrared (FT-ATR). Electron spectroscopy is, for example, X-ray Photoelectron (XPS) and mass spectroscopy includes Secondary Ion Mass Spectroscopy (SIMS). They can give an overview about chemical composition change of the wood, therefore, enabling to understand and analyse the changes. (Rowell, 2013)

Microscopic methods are helping to analyse causes of the appearance changes. For example, methods such as SEM (Scanning Electron Microscopy), CLSM (Confocal Laser Scanning Microscopy) and AFM (Atomic Force Microscopy) will describe physical properties of the wood surface from a very close range, thus giving valuable information for understanding the reasons of appearance changes. (Rowell, 2013)

All described methods are helpful for characterizing appearance changes of the wood. Better overview from changes can be gathered when multi-sensor approach is used.

2.3 Wood Protection

Bio-materials are degrading in outdoor conditions and this is holding back their widespread usage in building sector. Exterior environment creates challenging conditions for materials, therefore, it is reasonable to use wood materials with higher natural durability as stated in EN 350-2 (1994). In the past, problems of degradation were solved by using durable hardwood species (Hill, 2006). In developed countries, naturally durable wood species are not growing fast enough to satisfy the demand for durable wood products. Tropical hardwood species can be used but this causes concerns about exploitation as these species are usually from developing countries where regulations and supervision are not sufficient enough to prevent overusage (Walker, 2006). Therefore, need for durable wood species has increased. In proper conditions, wood will last for centuries. However, when wood is exposed to wood degrading factors then it needs protection (Forest Products Laboratory, 2010). Preservatives and modification are changing wood properties to improve its performance in challenging conditions.

Following chapters are describing different ways how to change wood properties and increase its weathering resistance.

2.3.1 Thermal Modification

Wood modification means a process where wood properties are improved but disposal of the produced material is not more hazardous to the environment than disposal of an unmodified wood. The aim of wood modification may be improvement in decay resistance, dimensional stability, improvement against weathering, etc. (Hill, 2006)

Thermal modification is commercially the most widespread wood modification process (Hill, 2006). It is executed in temperatures of 180 – 260 ˚C and because of high temperatures, wood characteristics (chemical structure, colour, weight, etc.) are changing. Reasons behind weight decrease of thermally modified wood are water loss and degradation of wood components.

Cellulose starts degrading over 165˚C and hemicellulose even earlier. Lignin is less stable to UV radiation but regarding the high temperatures, lignin is more stable than other wood components.

When wood is thermally modified, it turns darker. The more higher the treating temperature, the more darker a wood will be as illustrated in Figure 2.4. However, colour change is not permanent when wood is used in exterior conditions as it is prone to change its colour just like an unmodified wood. (Hill, 2006; Rowell 2013)

Figure 2.4. Colour of heat-treated pine (ThermoWood, 2003)

Properties of thermally modified wood are highly dependet upon the selected modification process. The most known commercialized thermal modification processes are ThermoWood (Finland), Plato Wood (the Netherlands), Oil Heat Treatment (Germany), Retification (France) and Le Bois Perdure (France). Main idea of these processes is the same – wood is heated in high temperatures to change its properties. However, treatment methods haves some methodical differences. Differences are:

- which temperatures are used for heating,
- how rapidly heating is executed,
- in which environment process is taking place,
- which wood species can be treated,
- catalysts used, etc. (Hill, 2006)

Thermal modification changes chemical structure of wood and that gives wood new properties. Positive changes are dimensional stability, resistance against bio-organisms and decaying. Negatives of thermally modified wood are increased brittleness, decrease of strength properties and low durability when in contact with the soil. (Hill, 2006)

There are disagreements in a literature overview about checking of thermally modified wood. Some experiments have shown that thermal modification reduces checking of the wood while some have found that it is same with unmodified wood. (Rowell, 2013)

Research works of Torvinen (2010) and Jämsa *et al* (2000) have stated that thermal modification does not affect the checking of the wood as it is vulnerable to chekcing just like an unmodified wood. Truusa (2015) and Vernois (2001) have found that checking of the thermally modified wood surface is reduced when compared to surface checks of umnodified wood. This is an interesting disagreement. Fortunately, experiments done during this Master Thesis should give more information about checking of thermally modified wood compared to natural wood as both categories are represented and checks are being measured.

Study of Tomak *et al* (2018) stated that after 48 months of weathering, thermally modified wood were in better conditions than natural wood. Thermally modified wood did not have any mold or fungi on it while unmodified wood had. Thermally modified wood had surface checks but in less extent than unmodified wood. Their study also stated that thermal modification cannot protect lignin degradation, therefore, thermally modified wood without a coating does not have a good colour durability in outdoor conditions.

Thermally modified wood cannot be used as bearing beams and in constructions that are in contact with the soil. Thermally modified wood can be used in terrace, windows, doors, sauna etc.

2.3.2 Impregnation

Idea of impregnation is to fill wood cells with chemicals to improve wood properties. Chemicals are “locked” in the wood cell, but they do not form new bonds. Impregnation modification gives dimensional stability, reduces hygroscopicity and protects against decay. (Rowell, 2013; Hill, 2006)

There are various methods how to impregnate wood. One option is a double vacuum method (low pressure method) where wood is put into autoclave and vacuum is applied to suck air out of the tank. Chemicals are flooding the tank and wood is left soaking. After that, vacuum is applied again to bring excess chemicals out of the autoclave. In the end of this procedure, wood should be touch try. Because no pressure or low pressure is used, penetration of preservatives is not very deep. Chemicals used are mainly solvents and as they are colourless, companies like to add dye to them so that people could get a confirmation about wood impregnation. (Coulson, 2012)

Another common method for impregnating is a vacuum pressure method (high pressure treatment) where pressure is applied between the two vacuum procedures to make sure that the biggest possible amount of treatment liquid would penetrate into the cells of the wood. That way it is possible to get a deeper penetration of chemicals. This method uses rather chemicals that are solved in water, therefore, these products are not recommended for joinery components as they are dimensionally less stable. These treatments usually contain copper, therefore, after impregnation, green tinge is characteristic for that wood. (Coulson, 2012)

Components of the chemical should be small enough to gain access to the wood cell. It is important that chemical would be non-leachable as wood preservatives should improve the properties of wood but at the same time they should not cause harm to the people or to the environment. (Hill, 2006; Forest Products Laboratory, 2010)

Preservatives meant for outdoors have mechanisms to keep chemicals inside the wood but still, some small percent of leaching has been found by recent studies. Ingredients in preservatives are potentially toxic but leaching happens in so small percentages that they are not able to create a biological hazard. (Forest Products Laboratory, 2010)

Many wood species are difficult to impregnate because of their cell structure. One example is spruce that can hardly be impregnated. However, heartwood of pretty much all species acts as same and is not accessible for impregnation. Figure 2.5 illustrates the impregnation of a pine wood where only sapwood area is impregnated as heartwood cannot be impregnated due to closed pores. (Hill, 2006)

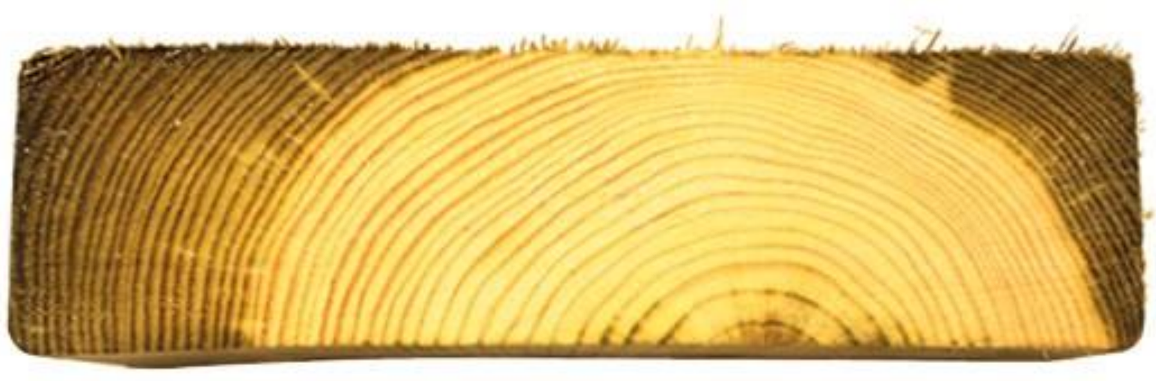

Figure 2.5. Pressure treated pine (SwedishWood, 2017)

Commercially the most likely treatments are aqueous delivery systems (Hill, 2006). One of the most famous preservative chemicals were CCA (Copper, Chromium and Arsenic). However, it is not favoured by the EU anymore as it contains arsenic and chromium. Nowadays it is not allowed to use CCA impregnated wood in domestic places such as children playground, animal gardens, etc. There are more environmentally friendly alternatives than CCA, such as chemicals called „azoles“. The most famous chemicals in that group are Propiconazole and Tebuconazole. (Coulson, 2012)

One treatment method that has been commercialised in wood impregnation is the reagent 1.3-dimethylol-4.5-dihydroxyethyleneurea (DMDHEU). This reagent was well used in textile industry and then brought over to the wood industry. This process improves dimensional stability, durability and reduction of moisture uptake of wood. However, brittleness and tendency to crack are the downsides of this impregnation. DMDHEU impregnation is marketed by the German company under the name of Belmadur. (Sandberg, 2017)

Study carried out by Pfeffner *et al* (2012) stated that DMDHEU impregnation could not prevent discolouration of the wood during weathering. However, DMDHEU impregnation was effective against fungal grow on the materials surface as there was remarkably less fungal grow on those materials than on natural materials.

Another treatment method that has been commercialised is known as the Indurite process. This process was invented by New Zealand company. They use water-soluble polysaccharide solution (soy and corn starch) to impregnate radiata pine. Usage of this wood is in exterior applications such as cladding and decking. (Sandberg, 2017)

Silicone treatment is also available. However, they have not been very popular, although procedure is commercially ready. Reasons may be that silicone is not able to penetrate the cell wall, therefore, gives not much improvement in dimensional stability. (Hill, 2006)

Impregnated wood can be used in bridges, decking, garden furniture, telephones posts, etc.

2.3.3 Chemical Modification

Term „chemical modification“ has been used differently by different authors in the past (Rowell, 2013). Author of this Thesis uses the same definition as Rowell and Forest Products Laboratory: „Chemical modification is a modification method where organic chemical reacts with wood cell wall components (i.e. hydroxyl groups) by forming new bonds (and by-products).“ Chemical modification enables to bulk the cell wall permanently with a chemical. This excludes simple impregnation treatments that do not form a bond, coatings, thermal modifications, etc. (Forest Products Laboratory, 2010; Rowell, 2013)

There are many ways to modify wood cell walls. Most common modifications are based on reaction with wood hydroxyl groups. One of those examples is acetylation, its reaction with wood hydroxyl groups is shown in Figure 2.6. Acetylation can be done by using acetic anhydride. During reaction, new bonds are formed and by-product acetic acid appears. Problem with the by-product is its bad smell but huge efforts have been put in to eliminate the by-product and those efforts have been successful. (Rowell, 2013)

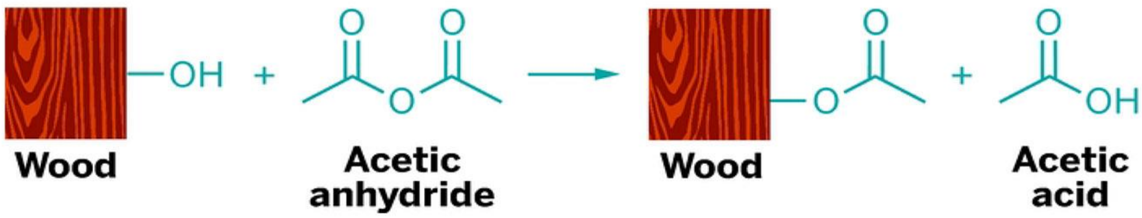

Figure 2.6. The reaction of wood acetylation with acetic anhydride (Sandberg, 2017)

Commercialization of chemically modified wood is most successfully done by Accsys Technologies (from the Netherlands) as they produce acetylated wood that is called Accoya. Acetylation is one of the most popular chemical modification methods. Accoya is made from plantation grown radiata pine from New Zealand and Chile. They use acetic anhydride in a vacuum-pressure cycle. Acetylation improves biological durability, dimensional stability, resistance against subterranean termites and marine borer attacks. Wood changes its colour minimally and is marketed as a „green“ product. It has a huge potential but limitations are materials as only radiata pine and alder are used for acetylation. Accsys Technologies are producing Tricoya, as well. It has similarities with Accoya but Tricoya is a trademark of Accsys Technologies for acetylated MDF panels. (Sandberg, 2017; Rowell, 2013)

Study of Schaller & Rogez (2007) stated that acetylation modification partly protects the lignin from photo-degradation in exterior conditions. However, it should be highlighted that acetylation protects only wood partly, therefore, there is still need for a coating that has sufficient UV light protection to avoid degradation of the wood as acetylation alone is not enough to make wood resistant against weathering.

Furfurylation is another method that has been commercialised. Furfurylation is done by reacting wood with furfuryl alcohol. Furfuryl alcohol is produced from agricultural wastes (i.e. sugar cane, corn cobs). Goal of this process is to improve dimensional stability and biological degradation of the wood. There are some disagreements if furfurylation is a chemical modification or impregnation modification but study of Li *et al* (2016) showed that furfuryl alcohol penetrates the wood cell walls during modification process, therefore, possibly being a chemical modification process. Furfurylated wood is produced under the name of Kebony and it is gaining popularity. Furfurylated wood is considered as a „green“ and safe for the environment. (Sandberg, 2017)

Research of Jirouš-Rajković and Miklečić (2018) stated that furfurylated wood turns grey during weathering (Figure 2.7). However, staining fungi and mould are not colonizing the surface of wood. Small surface checks may appear during weathering. Original colour of the furfurylated wood could be maintained by using UV protection oils or water-based acrylic paints.

Figure 2.7. Kebony after 3 years of weathering (Kebony, 2018)

Chemically modified wood has a wide range of applications. It can be used in window frames, doors, cladding, decking, etc.

2.3.4 Coatings

Coatings are an efficient way to protect wood and improve its properties. They can give wood a new colour, protect against moisture, UV-radiation, micro-organisms etc. (Bulian & Graystone, 2009). Wood without a coating turns grey eventually and that is why coatings are so highly rated. (Coulson, 2012)

The main goal of coatings is to protect wood surface, maintain the appearance and provide cleanability. Protection of the wood by a coating depends on variables such as thickness of the coating film, defects in the film, pigment type, chemical composition of the resin, length of exposure, etc. Nevertheless, coating can never be entirely moisture proof. Coating simply slows down the rate of moisture change in wood. (Tracton, 2007)

For outdoor conditions there are special finishes so before applying coatings it should be seriously considered what is the end usage of this product. Those coatings that are meant for indoor usage, should not be applied for exterior products because it is very likely they will not last long. (Bulian & Graystone, 2009)

Most popular wood finishing coatings are dye, oil, varnish, stain, wax, paint (Sandak A. & Sandak J., 2017). Finishes are classified as film-forming finishes (paints, varnishes, varnish stains, solid-colour stains) and penetrating finishes (oils, water repellents, solvent-borne stains). Another way of classification are opaque finishes (paints, solid-colour stains) and natural finishes (water repellents, semi-transparent penetrating stains, penetrating oils, varnishes). Finishes can be applied with brushes, sprays, rollers, pads, etc. (Tracton, 2007)

Paints are film-forming finishes. They provide efficient protection against UV light, erosion, wetting, hide wood defects and allow choosing preferable colour (Rowell, 2013; Tracton, 2007). This means that they are also hiding the natural grain of wood. Durability of the paint film depends on the interaction with the wood surface, how paint was applied and conditions that material will be in (Walker, 2006). Paints usually fail between the joints of wood pieces. Failing of the paint film layer allows access of water and water may be trapped in wood. This creates environment for decay fungi to appear, therefore, voids and defects in the film layer of the coating are reducing performance of a wood product. Voids and defects are also causing flaking and peeling of the film layer (Figure 2.8). Latex-based paints will allow some moisture movement and are flexible while oil-based paints provide good shield against water and moisture but will become brittle during time, thus not lasting long. (Tracton, 2007)

Figure 2.8. Flaking and peeling of the paint layer (Kaz, 2013)

Stains are less pigmented and / or dyed than paints. Therefore, they are not hiding wood grain completely (Figure 2.9). They are penetrating the wood surface and are porous to water vapour. They are non-film forming and are more preferred in outdoor conditions as penetrating stain will not peel off, instead they will fade off elegantly because of erosion (Coulson, 2012). Stains can protect wood against weathering for approximately 2 - 6 years (Rowell, 2013). Stains are alkyd or oil based and may contain preservatives. (Tracton, 2007)

Figure 2.9. Wood staining (Jensen, 2017)

Water repellent preservatives contain wax, a resin or drying oil and a solvent. They do not contain colouring pigments and can be used as natural finishes. However, inorganic pigments can be added to get a different colour, result is similar to the stains. Water repellent preservatives can be used as a pre-treatment before applying paint as they give paints a much-needed water protection in case of failure of the film (Rowell, 2013). During first years of usage, water repellents may have to be applied every year until wood reaches a stable colour. Afterwards, wood needs refinishing only when surface is going to be coloured by fungi. (Tracton, 2007)

Oils and varnishes are clear coating finishes. Generally, there is a rule that the more natural finish it is, the less durable it is. Natural oils are performing badly in outdoor conditions as they are providing food for bio-organisms (Forest Products Laboratory, 2010). They need an active maintenance to hold their performance. Varnishes are not good for outdoor conditions as without frequent maintenance they will allow stain and mould to appear (Coulson, 2012). They become brittle when exposed to the sunlight and start cracking and peeling. Performance of oils and varnishes can be improved if water repellents or UV stabilizers are added. (Tracton, 2007)

Study of Turkoglu *et al* (2015) investigated colour stability of impregnated and varnished wood. Results indicated that impregnated + varnished wood were much colour stable than unmodified wood. Only varnished and not impregnated wood showed less colour stability than impregnated + varnished wood. Therefore, hybrid modification should be considered when weathering.

Usage of coated wood is very wide as they can be used basically everywhere. They protect wood and are usually very efficient and easy to apply, that is why they are so popular.

3 MATERIALS AND METHODS

The experimental part of this Master Thesis is done in collaboration with the BIO4ever project. BIO4ever is an international project and its overall goal is to “fulfil gaps of lacking knowledge on some fundamental properties of novel bio-based building materials“ (Sandak, 2019).

Author of this Thesis contributes to the project by evaluating weathering resistance of bio-based materials under outdoor conditions in Tallinn, Estonia. Data gathered during experiments will be used by project leaders to develop a software that is simulating performance of bio-based facade materials.

3.1 Materials

Materials under evaluation have been gathered from companies all over the world (Figure 3.1). Specimens were sent by 31 companies from 17 different countries. Most of the companies locate in Europe but some specimens were sent from the Central America and New Zealand, as well. Evaluation of the materials by weathering is taking place in Tallinn (Estonia) and San Michele (Italy). Durability of materials in field tests is measured in San Michele (Italy), Oleron Island (France) and Guadeloupe (France). Red stars in Figure 3.1 are marking companies that sent their specimens and yellow stars are marking countries where experiments are taking place.

Figure 3.1. Countries participating in the BIO4ever project (A. Sandak, 2017)

Companies sent their materials to the Trees and Timber Institute of the National Research Council of Italy (*CNR – IVALSA*) that is the leading member of the BIO4ever project. Materials were marked in Italy and sent to Estonia to evaluate the weathering resistance of bio-based materials. Length of samples is mainly 150 mm, width 75 mm and thickness 20 mm.

There are 120 test specimens under evaluation. Materials have been treated variously, therefore, they have been categorised into 7 main groups: natural, chemically modified, composites, coated, impregnated, thermally modified and hybrid modified (modified with more than 1 method). Categorisation of materials and examples from these categories are introduced in Table 3.1.

Table 3.1. Materials under evaluation

Wood Modification Technology	Samples	Number of Tested Materials
Natural	Wood, bamboo	19
Chemical Modification	Acetylation, furfurylation	5
Composites	Panels, bio-ceramics, tricoya, wood plastic composites	7
Coating & Surface Treatment	Different coatings, carbonized wood, nanocoatings	16
Impregnation	DMDHEU, Knittex, Madurit, Fixapret	28
Thermal Modification	Vacuum, saturated steam, oil heat treatment	20
Hybrid Modification	Thermal treatment + coating, thermal treatment + impregnation, acetylation + coating etc.	25

Group of natural materials includes popular European wood species such as pine, spruce oak, etc. Some tropical hardwood species and bamboo samples also belong to this group. Chemically modified specimens include acetylated and furfurylated materials. Category of composites consists of a ceramic panel, Tricoya, wood plastic composite, fibreboard and particleboard. Coated and surface treated specimens include variously finished materials such as painted, oiled, waxed, varnished, nano-coated materials. Impregnated materials are one of the largest group and it includes, for example, AATMOS ([3-(2-Aminoethylamino)propyl]trimethoxysilane), TA (Timbercare Aqua), Fluorosilane, DMDHEU (1.3-dimethylol-4.5-dihydroxyethyleneurea), Knittex, Madurit and Fixapret impregnated materials. Thermally modified group (TM) includes various popular wood species that have been modified thermally. Hybrid modification is the group where more than one modification method is used on samples. There are many different modification combinations used, for example, acetylation + coating, thermal modification + impregnation, thermal modification + coating, impregnation + biofilm, impregnation + oil, etc.

Impregnated materials have the most specimens under evaluation with 28 samples. Next categories are hybrid modification (25 samples), thermal modification (20 samples), natural (19 samples), coating and surface treatment (16 samples), composites (7 samples) and chemical modification (5 samples). Figure 3.2 illustrates the proportion of all the categories that are being evaluated during weathering tests.

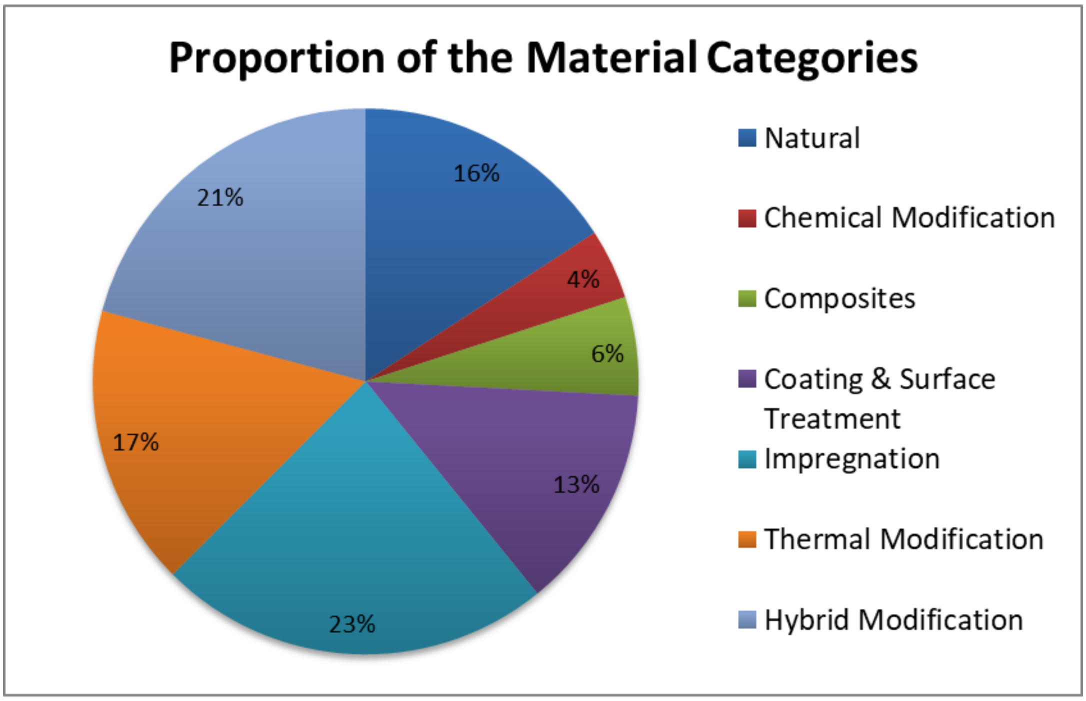

Figure 3.2. Proportion of the material categories

From the figure above, it is possible to see that 2 categories (impregnation and hybrid modification) have the most materials evaluated while chemically modified and composites are clearly the least represented groups in this experiment.

In general, a large number of different bio-based materials are under evaluation and this should create good conditions for comprehensive analysis.

3.2 Methods

Methods for evaluation have come from COST Action FP1303 instructions that have been put together by various specialists from the European research organisations and universities (Brischke *et al*, 2014). Idea of this instruction is to set specific rules how experiments should be conducted. It enables to compare results of different tests as experiments are all conducted in the same manner.

Experiments for this thesis are taking place in Tallinn, Estonia. They started in 14.03.2017 and last data for the thesis was gathered in 26.03.2019 as goal of 2-year weathering was achieved. Materials are located on the stand (Figure 3.3) at the TalTech Laboratory of Wood Technology outdoor weathering site (59°23'50.6"N 24°39'24.0"E). Stand is in a 45 degree angle so it exposes materials to the sun and enables rain water to move away. Water removal is important as otherwise leaching could occur and materials could start affecting each-others performance. Experiments could be also considered as natural accelerated weathering of facade materials as facades are mostly vertical and degradation of facade materials is much faster in a 45˚ angle than in a vertical weathering as was introduced in literature overview. Specimens are attached on the stand with 10 mm staples. Stand is facing the south so that materials would be exposed to the sun maximally.

Figure 3.3. The stand of specimens in TalTech (Southern exposure, 59°23'50.6"N 24°39'24.0"E)

Evaluation of materials is done by colour and check measurements. Colour is measured for every first 6 weeks, then for the first 6 months after every 4 weeks, and then after every 6 months as shown in Table 3.2. Timetable was made according to COST FP1303 instructions (Brischke *et al*, 2014). Second week measurements were cancelled due to bad weather conditions. Additional measurements were conducted in spring 2018 to notice any seasonal colour fluctuations but that kind of trend was not noticed, therefore, it was continued with the COST FP1303 schedule (Brischke *et al*, 2014).

Table 3.2 Timetable of Measurements ("+" (green) – Measurements conducted according to instructions; Cancel (red) – Measurements cancelled; Extra (yellow) – Extra measurements taken; "-" (white) – Measurements not planned)

	Time of Exposure	Photo	Measurement of Checks	Colour Measurement
Week	0	+	-	+
	1	+	-	+
	3	+	-	+
	4	+	-	+
	5	+	-	+
	6	+	-	+
Month	2	+	-	+
	3	+	+	+
	4	+	-	+
	5	+	-	+
	6	+	+	+
	7	+	-	-
	8	+	-	-
	9	+	Cancel	-
	10	+	-	-
	11	+	-	-
	12	+	+	+
	13	+	-	Extra
	14	+	-	-
	15	+	+	Extra
	16	+	-	-
	17	+	-	-
	18	+	+	+
	19	+	-	-
	20	+	-	-
	21	+	Cancel	-
	22	+	-	-
	23	+	-	-
	24	+	+	+

Checks of the materials are measured after every 3 months (Table 3.2). In Estonia, all winter period measurements were cancelled as materials were under snow and ice or they were so wet that it was not possible to get adequate results.

Pictures of the specimens are taken for the first 6 weeks in every week and then in every month for 2 years (Table 3.2). Photos were taken by Triinu Poltimäe and assisted by the author of this thesis.

3.2.1 Colour

One way to characterize the appearance change of a material is to measure its colour. It could be read from literature overview where study of Dimitriou *et al* (2017) stated the importance of the colour for human perception as gloss and roughness changes were not that relevant from human perspective. Therefore, colour is an important factor when evaluating materials appearance.

In this study, selection of colour measurement methods were inspired by COST FP1303 instructions that recommended to use the International Comission of Illumination (*CIE – Commission internationale de l'éclairage*) *L*a*b** (Lab) color space method, also known as CIELAB (Brischke *et al*, 2014).

Colour space has three axes that are defining the exact colour in a colour space (Figure 3.4). Axes are *L**, *a** and *b**. *L** axes represents the light and dark scale of a specimen. Figure 0 is referring to the dark colour while 100 is referring to the light colour. Axes *a** shows specimen colour in the scale of red (100) – green (-100) and *b** in the scale of yellow (100) – blue (-100). (Brischke *et al*, 2014)

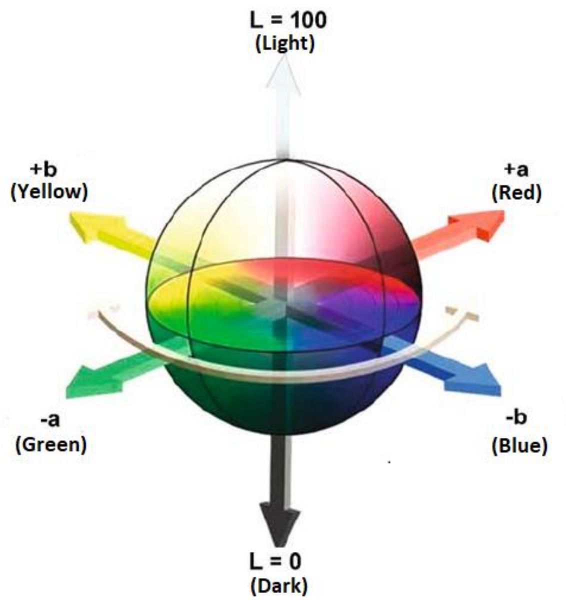

Figure 3.4. Colour space (Singh *et al*, 2014)

Colour change in the colour space is referred in Units of Measure (U/M). Colour change is calculated following these equations:

$\Delta L = (L_i - L_1)$ (3.1)

where ΔL – colour change in L^* axis,

L_i – colour coordinate after latest measurements in L^*axis,

L_1 – colour coordinate before the exposure in L^*axis. (Brischke *et al*, 2014)

$\Delta a = (a_i - a_1)$ (3.2)

Where Δa - colour change in a^* axis,

a_i – colour coordinate after latest measurements in a^*axis,

a_1 – colour coordinate before the exposure in a^*axis. (Brischke *et al*, 2014)

$\Delta b = (b_i - b_1)$ (3.3)

where Δb - colour change in b^* axis

b_i – colour coordinate after latest measurements in b^*axis,

b_1 – colour coordinate before the exposure in b^*axis. (Brischke *et al*, 2014)

Symbol ΔE is referring to an overall colour change in a colour space and it is calculated with the next equation:

$$\Delta E = \sqrt{(\Delta L)^2 + (\Delta a)^2 + (\Delta b)^2} \quad (3.4)$$

where ΔL – colour change in L^* axis,

Δa – colour change in a^* axis,

Δb – colour change in b^* axis. (Brischke *et al*, 2014)

Colour measurements in this experiment were done with Minolta Chroma Meter CR-121. It measures materials colour by the reflecting light. To measure colour every time from the same place, three marks where done on the specimen as showed in Figure 3.5. Marks were made 30 mm from the sides and in the centre.

Figure 3.5. Marking of the colour measuring spots (Brischke *et al*, 2014)

3.2.2 Checks

Another method for evaluating appearance change of specimens is measuring checks that have emerged on a material surface. Checks are measured only on the surface area as stated in the COST FP1303 instructions. Side and downside checks are not being measured. Checks on a material are described by their quantity (checks shorter than 5mm are not taken into account), mean maximum width and total length as stated in the COST FP1303 instructions.

Checks are measured with an Avongard Check Width Gauge (Figure 3.6) that is specially meant for the check measurements. From the Figure 3.6 it can be seen that the upper scale of the ruler is meant for measuring the width of checks while the lower scale is meant for measuring the length of checks.

Figure 3.6. Check Width Gauge

3.2.3 Photos

All materials under evaluation are pictured every month so it would be possible to see how their appearance has changed during time. Photos are taken with CanonEOS 450D camera and in one picture there are 6 specimens (Figure 3.7). CameraTrax 24ColorCard is used so it would be possible to adjust light and brightness afterwards for comparison of changes. Photos were taken by Triinu Poltimäe and assisted by the author of this thesis.

Figure 3.7. Example of how pictures were taken (Triinu Poltimäe, 2017)

It is possible to evaluate colour change of materials from pictures as usage of colour palette during experiments makes it possible to adjust light and brightness adequately. During writing of this Master Thesis, TalTech Laboratory of Wood Technology did not have the MATLAB program to measure colour change from pictures but there is a possibility that for future analysis, access to this program will be acquired.

Colour change collages made during this master thesis are not brightness adjusted, therefore, are only for illustrative purposes as visual changes may be strongly affected by temporary weather conditions.

3.2.4 Weather Data

Weather data is a valuable component of describing the environment where materials have been in. Detailed information about the following parameters to describe the environmental conditions near the experiment site is needed:

- Precipitation,
- UV index,
- Average air temperature,
- Minimum air temperature,
- Maximum air temperature,
- Average relative humidity. (Brischke *et al,* 2014)

These parameter requirements have been chosen as it is a standard from COST Action FP1303 instructions. (Brischke *et al,* 2014)

Weather data for this experiment is obtained from the Estonian Weather Service´s weather station in Harku. It is the nearest weather station to the exposure site, locating 3,2 km from the experiment stand.

4 RESULTS AND ANALYSIS

Weathering results of 120 bio-based facade materials were gathered during 2-year weathering period. Appearance change of all the materials is shown in Figure 4.1.

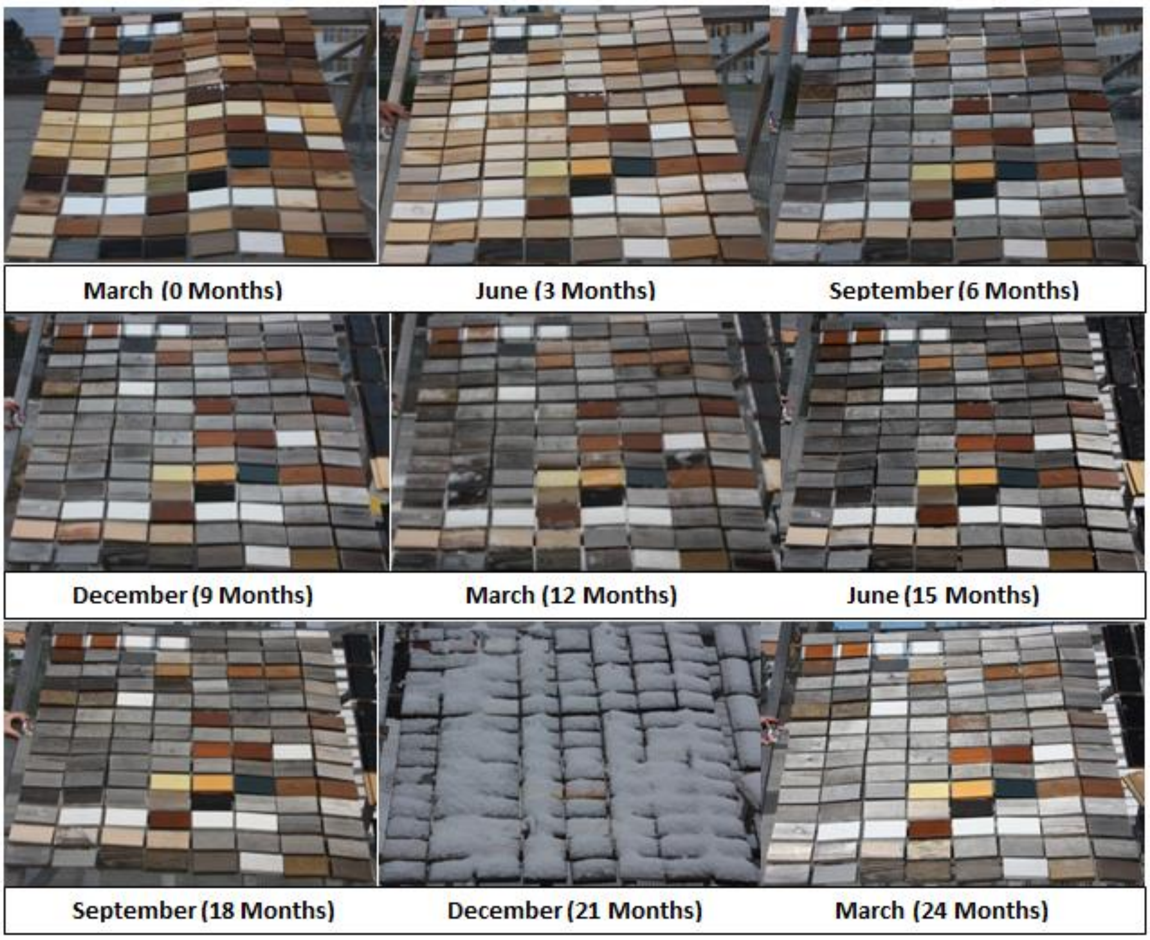

Figure 4.1. Appearance change of all the materials

From figure above, it is possible to see that after 6 months of weathering, majority of materials have turned into greyish colour. Visually, only approximately 20 materials have managed to held their original appearance after 2-year weathering. However, as visual assessment is largely subjective, other methods (colour change and surface check measurements) were applied to characterise the appearance change of materials.

The intensity of weathering is dependent upon timber species, design solutions, finishing technology and specific location (Sandak *et al*, 2018b). Angle of exposure affects the rate of weathering also as was stated in literature overview. Confirmation of this can be seen in Figure 4.2 where results of 1-year weathering in Italy, San Michele are presented.

Figure 4.2 Experimental samples during natural weathering in San Michele, Italy (southern exposure, vertical stand) (Sandak *et al*, 2018c)

In Italy, exactly the same materials were used and samples were set out exactly in same order as in Estonia. It can be seen that after 1 year of weathering in Italy, not a single material became grey, while in Estonia, majority of the materials have turned grey already after 6 months of weathering. Change in appearance of the materials has happened in Italy also but nowhere near as much as in Estonia. Of course, weathering conditions are different and this has an effect but the main reason why difference is so drastic is the angle of exposure. In Italy, vertical stand was used for weathering. Degradation in a vertical exposure happens twice as slow as in 45˚ angle, as could have been read previously from literature overview. Difference in exposure angles makes comparing of results slightly more difficult. However, it confirms the fact that weathering is much faster in a 45˚ exposure angle than in a vertical exposure.

Following chapters will present results of the colour change and emergence of surface checks on wood after 2-year weathering. In addition, weather conditions of materials exposure time are being presented.

4.1 Weather Conditions

Weather in the test site varied throughout the year as Estonian climate has 4 seasons. Precipitation and Relative Humidity are shown in Figure 4.3. It could be seen that in both years, spring and beginning of the summer were less rainy while the end of summer and autumn were more rainy. The biggest monthly precipitation was witnessed in August 2017 when 180 mm poured down. The most dry month was May 2018 with only 5,5 mm of rain. Relative humidity was the highest in November 2017 (93,7 %) and the lowest in May 2018 (57,3 %). Relative humidity was in both years lowest in the end of spring and highest in the end of autumn. Change of relative humidity had a pattern and it repeated from year to year.

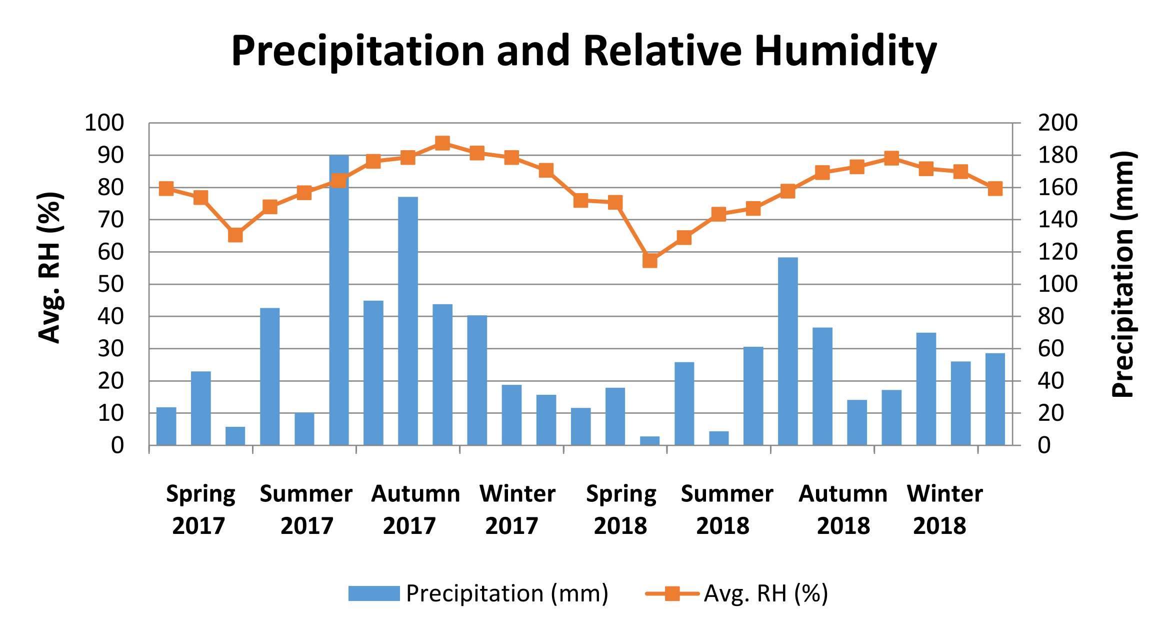

Figure 4.3. Precipitation and relative humidity during 2-year weathering (Harku Weather Station)

Air temperature during exposure times can be seen in Figure 4.4. Lowest air temperature was witnessed in February 2018 with -17,5 ˚C. Highest temperature was in July 2018 with 34,2 ˚C. Average air temperature was in the range of -6 ˚C (February 2018) to 20,4 ˚C (July 2018). Highest air temperatures were witnessed during summer times while lowest were in winter.

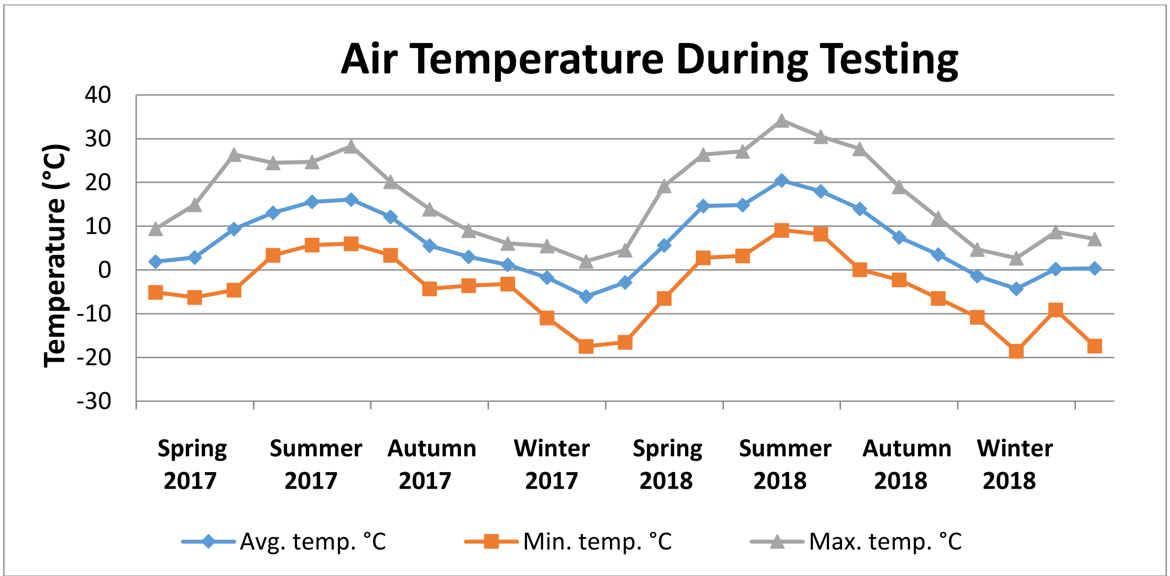

Figure 4.4. Air temperature during 2 year weathering (Harku Weather Station)

Maximum UV indexes recorded during weathering tests can be seen in Figure 4.5. UV indexes were highest during summer times, reaching the most highest point in July 2018 with an UV index of 7,1. Lowest UV indexes were recorded in winter times and the lowest point was in December 2018 with an UV index of 0,2 that is considered extremely low. Change of UV index is pretty well predictable as it changed smoothly and constantly.

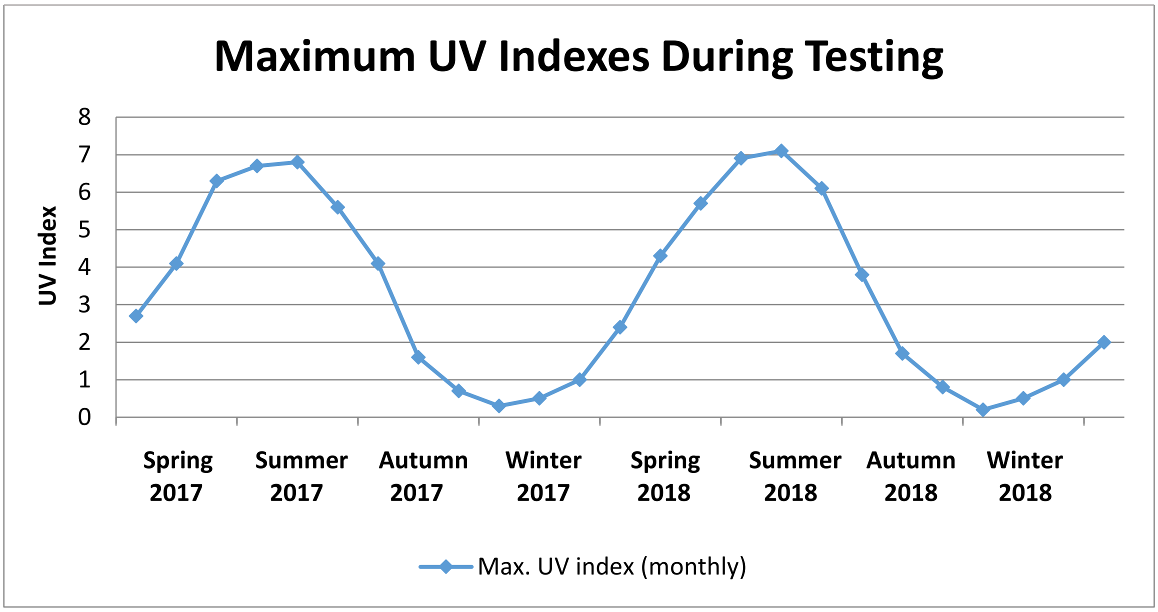

Figure 4.5. UV indexes during 2 year weathering (Harku Weather Station)

In conclusion, weather conditions were variable during the whole year. The end of spring were low in relative humidity and rain while the end of autumn was high in relative humidity and rain. Air temperature varied from -17,5 ˚C in winter to 34,2 ˚C in summer. UV index showed high UV radiations during summers (7,1) and extremely low UV radiations during winter times (0,2). High fluctuation of the climate conditions makes it challenging for materials to keep their original appearance.

4.2 Colour

Colour change of 120 materials was evaluated during outdoor experiments. Highest colour changing material was pine, impregnated with nano TiO_2 and coated with lineseed oil (*ΔE* = 40,8 Units of Measure). The lowest colour changing material was Accoya (*ΔE* = 1,3 U/M). Arithmetic average of the *ΔE* by all colour changed specimens was 18,8 U/M while median average was 18,5 U/M. As wide range of samples were evaluated during this experiment, previously mentioned *ΔE* figures can be used as indicators to help understanding whether the colour change of a material was high or low.

Materials were divided into 7 different groups as was described in the Materials and Methods chapter. Colour change of all the materials is in Appendix 1 but each group is investigated separately in the chapters below. Every colour change chapter includes figures where materials are ranked by the colour change as highest colour changing materials are in the top and lowest colour changing materials are in the bottom of the figure legend list. Chapter 4.2.8 points out materials that have had the highest and lowest colour changes during 2 years of weathering.

4.2.1 Natural

Group of natural materials consisted mainly from popular Europe tree species such as pine, spruce, oaks, poplar, etc. In addition, bamboo and plantation teak samples are also included in this category. All together there were 19 samples in this group.

Colour change of the natural materials can be seen in Figure 4.6. Natural materials changed their colour relatively much as only 4 samples stayed below the *ΔE* median average (18,5 U/M). Lowest colour changed natural materials were oak, poplar, bamboo and beech while the highest colour changed natural materials were pine, spruce and larch samples. Plantation teak materials changed their colour less than pine, spruce and larch but more than oak, poplar, bamboo and beech samples. Colour change of natural materials stabilised after 6 months of exposure.

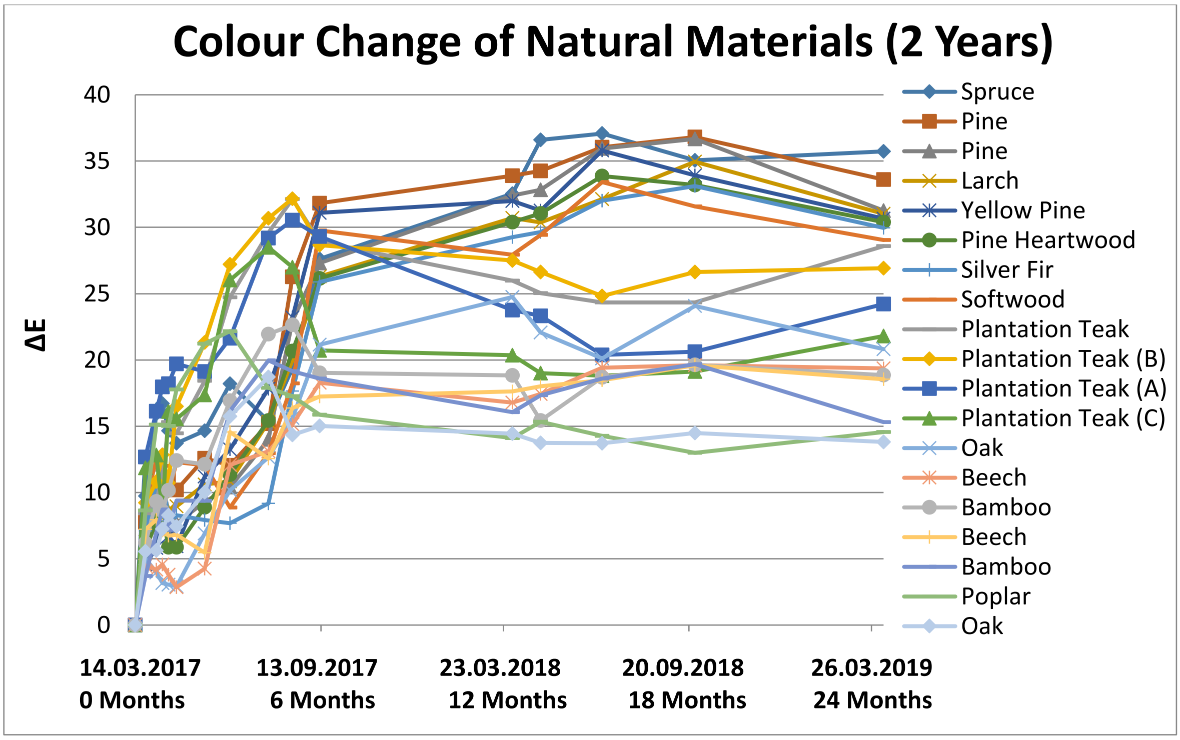

Figure 4.6. Colour change of natural materials

Study of Oberhofnerova *et al* (2017) did a similar experiment where natural wood species were tested in outdoor conditions. Their experiments were done in Central Europe for one year. Their results showed that spruce, pine and larch were one of the largest colour changers while oak was the lowest, similar for results that author of this thesis received. Only remarkable difference was in poplar colourisation as authors results showed that poplar was one of the lowest colour changing natural material while Oberhofnerova *et al* (2017) results showed that poplar was one of the highest colour changer. Results may differ because only one poplar specimen was used in both studies.

Oberhofnerova *et al* (2017) results showed that *ΔE* of spruce after one year of weathering was 34,1 U/M and *ΔE* of oak was 23,0 U/M. Author of this thesis got results after one year of weathering that spruce *ΔE* was 37,0 U/M and *ΔE* of oak was 14,4 U/M. In general, results are similar but there are many variables (geographic location, specific wood type, etc.) that are causing small differences.

Colour change of natural spruce was analysed more precisely in the *L*a*b** coordinate scale (Figure 4.7).

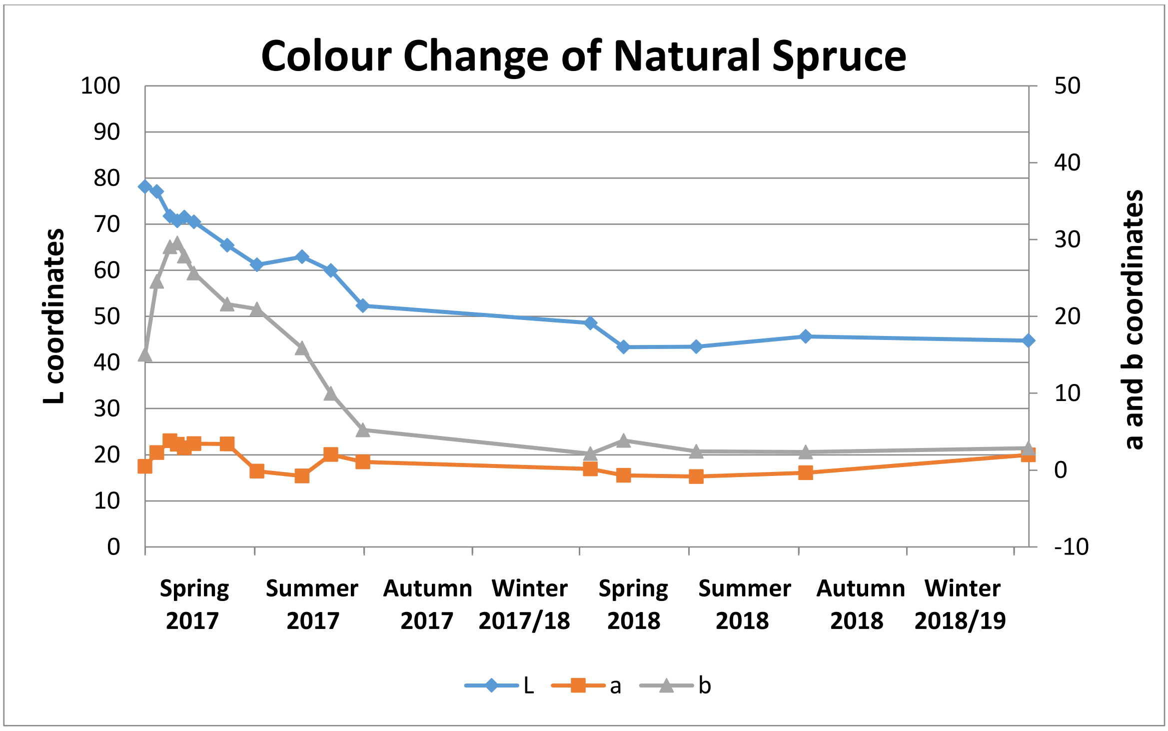

Figure 4.7. Colour change of the natural spruce in *L*a*b** coordinate scale

From that figure it can be seen that spruce got darker during time as *L** (dark – light) results have decreased. Coordinate of *a** (green - red) axis has been relatively stable during weathering while *b** coordinate (yellow – blue) shows that spruce has turned more yellower in the first month of weathering and after that, started to go more in the darker, blue scale. Study of Oberhofnerova *et* *al* (2017) stated that initial increase in *b** values may indicate degradation of lignin while final decrease of *b** coordinate may indicate leaching of decomposed lignin and extractives, therefore, causing the colour change. This may be the reason why spruce sample in this experiment changed its colour rapidly in one direction in the beginning of the exposure and after one month started to change its colour into another direction in *b** coordinate scale. Colour change of spruce stabilised after 6 months of weathering.

Collage made about natural spruce (Figure 4.8) confirms that colour of the specimen went more yellowish during first month of weathering and rapidly lost its yellowness for the second month. It also confirms that colour change has been relatively stable after sixth month as material has been evenly greyish since then. However, it should be reminded a notification from the Methods chapter: colour change collages made during this master thesis are not brightness adjusted, therefore, are only for illustrative purposes as visual changes may be strongly affected by temporary weather conditions.

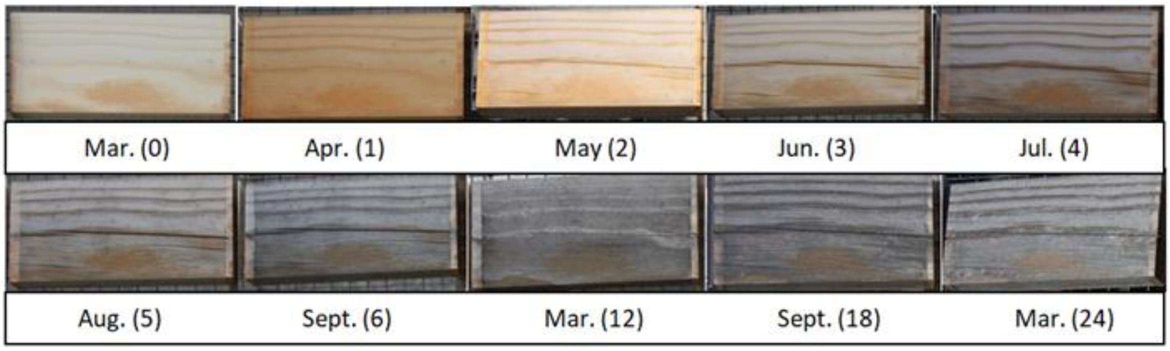

Figure 4.8. Visual colour change of natural spruce (Legend: Calendar Month (Time of Exposure in Months))

It can be concluded that natural wood does not have a high colour stability but from natural wood, oak is one of the most colour durable species and spruce is one of the lowest.

4.2.2 Thermal Modification

Group of thermally modified materials consists of various wood species from Europe and tropical areas that have been thermally treated.

Colour change of thermally modified materials can be seen in Figure 4.9. In general, thermally modified specimens changed their colour moderately. There were 20 thermally modified materials, 9 of them changed more colour than average material from the 120 samples while 11 of them changed less colour. The biggest colour change of thermally modified wood happened on frake (25 U/M) and smallest on spruce (7 U/M).

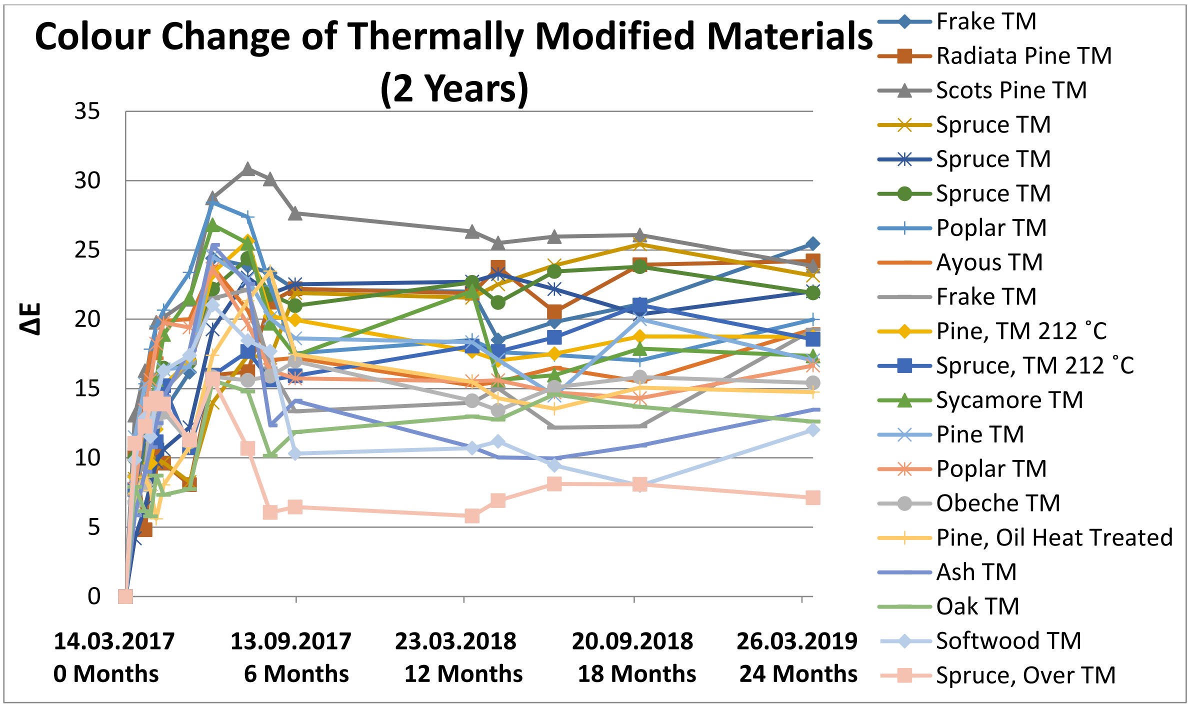

Figure 4.9. Colour change of thermally modified materials

It was characteristic for thermally modified wood to change its colour rapidly during first 3 - 4 months of exposure. After first 4 months there was a decrease in colour change and colour of materials stabilised.

Study of Tomak *et al* (2018) compared weathering results of thermally modified and untreated wood after 48 months. They found that thermally modified materials demonstrated considerably less colour change than unmodified wood. Author of this thesis can agree with that as previously presented results are proving that thermal modification improved colour stability of materials compared to unmodified samples. However, colour change of thermally modified wood is still remarkable.

It can be concluded that colour change of thermally modified materials was moderate as they changed less colour than unmodified wood but more colour than well protected (i.e. surface modified) wood materials.

4.2.3 Impregnation

Group of impregnated materials consisted from 28 samples. Colour change of these materials can be seen in Figure 4.10. It can be said that in general, impregnated materials changed their colour very much. Out of 28 impregnated materials, only 3 changed their colour less than an average sample. Biggest colour changing impregnated materials consist of AATMOS, fluorosilane and TA impregnations and combinations of them. Two samples: beech treated with PLA (poly-lactic acid) and softwood treated with CEA (Copper Ethanolamide) held their colour significantly better than other impregnated materials. In addition, Knittex, PBS (poly-butylene succinate) and Madurit impregnations are one of the lowest colour changed impregnated materials, as well. Colour change of impregnated materials developed rapidly during first 6 months, then it started to stabilise.

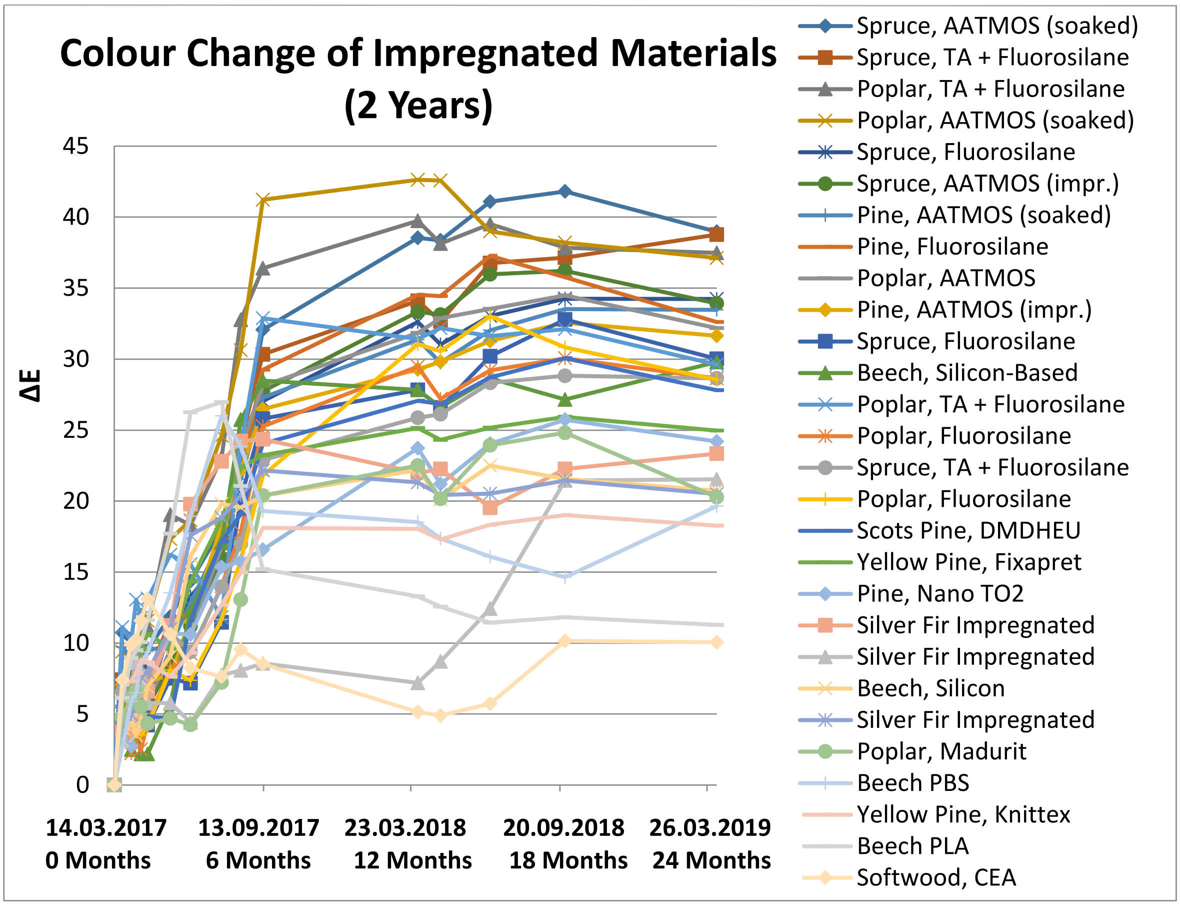

Figure 4.10. Colour change of impregnated materials

The biggest colour changer of impregnated materials was AATMOS impregnated spruce. AATMOS is a colourless silane based liquid that should prevent fungi. Study of Broda *et al* (2018) confirmed that AATMOS treated wood has antifungal resistance properties but when only AATMOS treating was used then this chemical appeared to leach out from the wood during time and wood lost its antifungal properties. Therefore, reason behind the high colour change of AATMOS soaked wood may be leaching of the chemical that left natural wood exposed to weather conditions.

Other bad colour stability materials were impregnated with TA (TimberCare Aqua) and Fluorosilane. TA is a colourless preservative that prevents damage of insects, decay and fungi (Hemel, 2016). It may be good at its goal to protect wood from fungi but as results show, it has a really bad colour stability. Fluorosilanes are making wood hydrophobic (NanoProtect, 2017). Therefore, goal of TA and Fluorosilane is to protect wood from decay, fungi, insects and water. Reason why AATMOS, TA and Fluorosilane preservatives could not prevent discolouration may be the fact that their focuses are on making wood resistant against fungi and decay but not against UV radiation and other weather factors, therefore, they are not meant for preventing discolourisation.

Best colour stability from impregnated materials were on CEA (Copper Ethanolamine) and PLA (Poly-Lactic Acid) samples. Study of Thaler & Humar (2014) stated that copper compounds are extremely prone to leaching but ethanolamine decreases leaching as it fixes copper compounds more firmly in wood. It also stated that leaching of the material is affected largely by the method of treatment as superficial treatments were more prone to leaching than vacuum pressure methods. It is likely that vacuum pressure method was used for impregnating wood with CEA, therefore, these two factors might have affected colour stability of wood positively when compared with other materials.

Study of Turkoglu *et al* (2015) stated that it is generally known that copper-based wood preservatives prevent photodegradation. Photostabilization of wood by copper compounds may be explained by reduced delignification during weathering (Temiz *et al*, 2005). That would explain why CEA impregnated wood had the best colour stability from impregnated materials.

PLA sample was investigated also to understand the reasons behind colour change. Figure 4.11 shows the colour change of PLA treated beech in *L*a*b** coordinate scale.

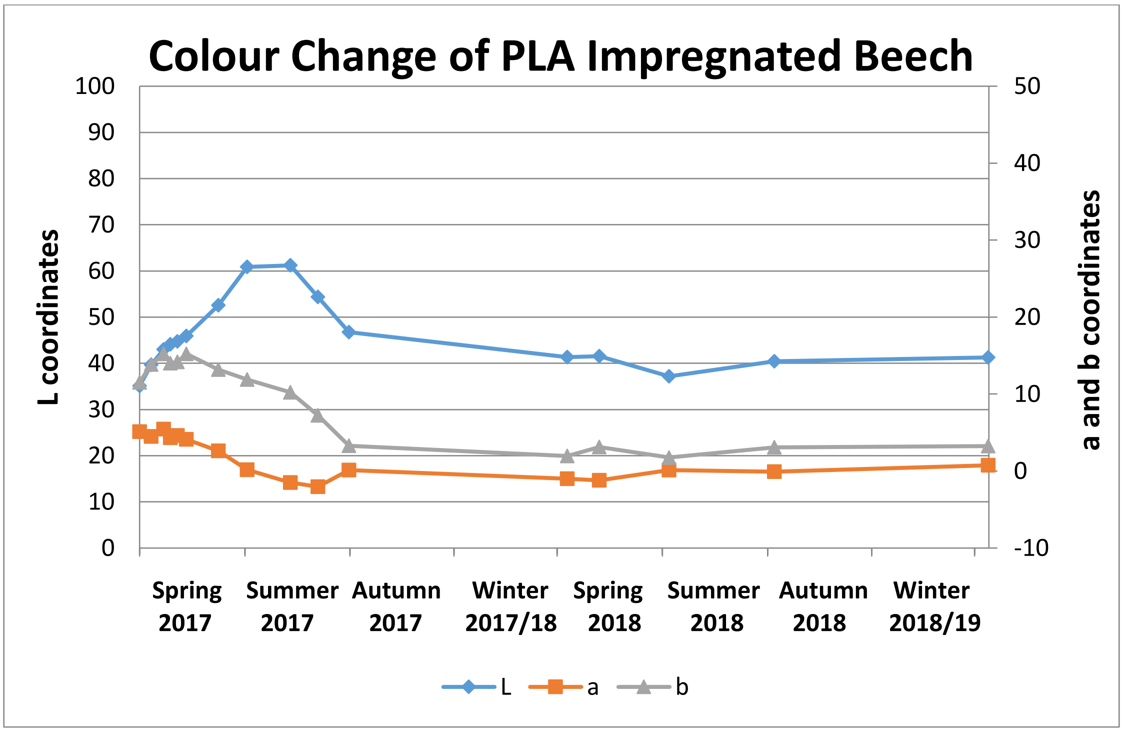

Figure 4.11. Colour change of PLA impregnated beech

From the figure above it can be seen that PLA impregnated beech has changed its colour lighter during 3 – 4 months of weathering, after that, started to get slowly darker again. This kind of behaviour is characteristic for beech wood as similar curve happened for natural and acetylated beech, as well. However, various other wood species (i.e. spruce) started to get lighter immediately and did not have that kind of curve. Scale of green to red (*a**) shows that material has been relatively stable in that coordinate but *b** has dropped 10 U/M during weathering. This may be a sign of delignification as was stated in Oberhofnerova *et al* (2017) study.

In conclusion, impregnated materials have not held their colour well. Reason why preservatives could not prevent discolouration may be the fact that their focuses are on making wood resistant against fungi and decay but not against UV radiation and other weather factors. In addition, leaching of coloured impregnation chemicals is likely to affect colour change of materials, as well.

4.2.4 Chemical Modification

Chemical modification group is represented with the smallest amount of materials – 5. It consists of acetylated and furfurylated (Kebony) materials. Colour changes of chemically modified materials are shown in Figure 4.12. They have held their colour relatively well as all specimens are under the overall *ΔE* median average. Kebony has kept its original colour more firmly than acetylated materials.

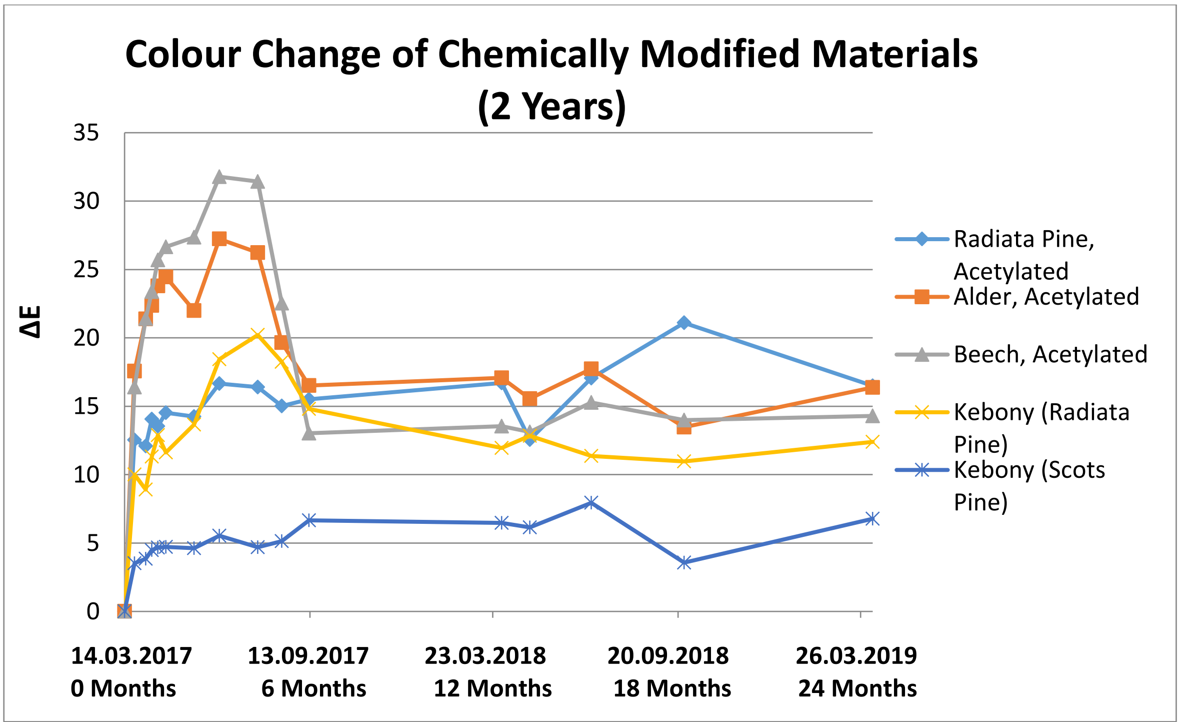

Figure 4.12. Colour change of chemically modified materials

Acetylated materials changed their colour rapidly during first 4 months of exposure but after that, started to change their colour back to their original colour and colour change stabilised after 6 months. During first 4 months of exposure, two acetylated materials where undoubtedly the fastest colour changing materials from 120 samples that are being examined. Therefore, reason behind quick colour change should be examined more closely. Acetylated Beech was chosen by the author for a more precise *L*a*b** examination (Figure 4.13).

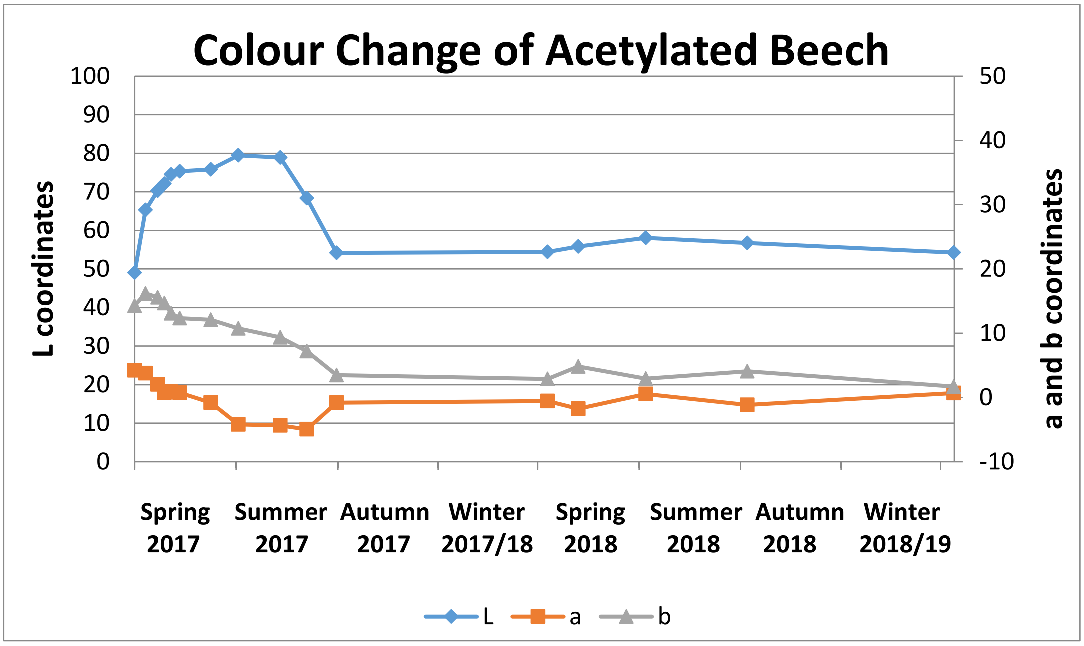

Figure 4.13. Colour change of acetylated beech

From the figure above, it can be seen how acetylated beech specimen has turned lighter in the *L** coordinate scale and after 4 months of weathering started to get darker. Slight rise in yellow scale (*b**) happened also but then it started to turn for a more darker colour (blue scale). After 6 months of weathering, colour of acetylated wood has been really stable. Reason behind the big curve in *L** scale in first 4 months may be the characteristic of beech wood as natural beech wood and PLA impregnated beech wood behaved similarly.

Collage about the colour change of acetylated beech was made, as well (Figure 4.14). Collage illustrates why acetylated beech had such a large curve in *L** axis during first month of exposure. It can be seen that material has turned significantly lighter after already 1 month of exposure and has changed its appearance completely. Fluctuations in appearance after sixth month are mainly affected by the weather conditions where pictures were taken (cloudy, sunny, etc.).

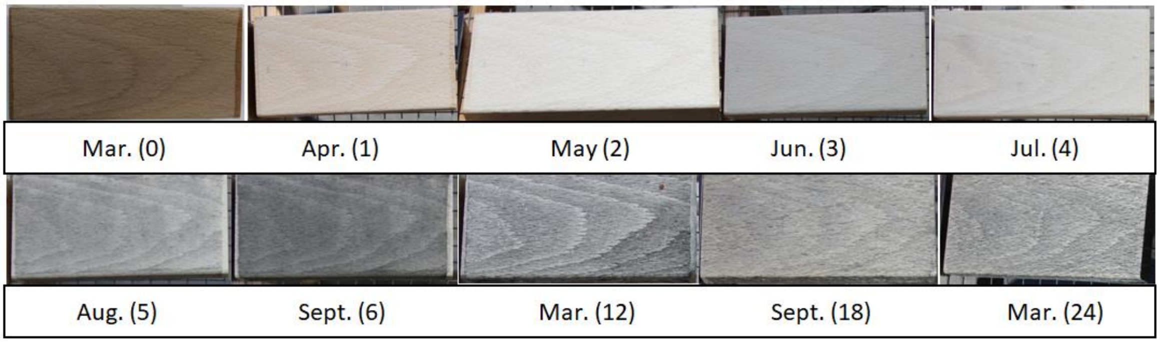

Figure 4.14. Visual colour change of acetylated beech (Legend: Calendar Month (Time of Exposure in Months))

Study of Temiz *et al* (2007) of furfurylation and study of Rowell (2006) of acetylation stated that chemical modification improves colour stability of the wood. Author of this thesis got similar conclusions for Kebony as colour stability has been improved. However, acetylated wood had high fluctuations in colour during initial stages of weathering. Later, colour changes stopped and have been stable since.

4.2.5 Surface Modification

Group of surface modified materials consists of 16 specimens (Figure 4.15). It contains various surface modification methods such as solvent-based coatings, water-based coatings, oils, wax, etc. Materials that have been surface modified have held their colour well as there are only 2 samples that have changed their colour more than an average specimen: nanocoated pine (27 U/M) and waxed oak (23 U/M). Coatings that are meant for windows have held their colour very firmly when compared to other materials. Not a significant difference was noticed between water and solvent based coatings.

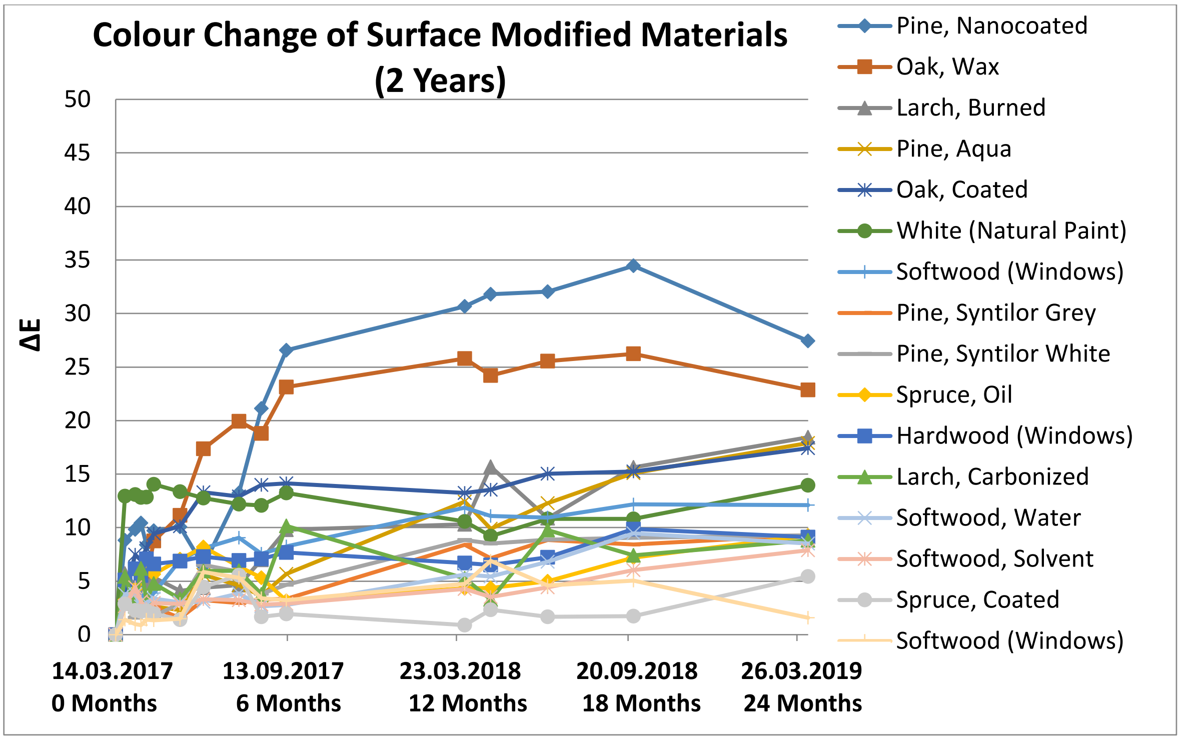

Figure 4.15. Colour change of surface modified materials

Similar experiment was conducted by Grüll *et al* (2014). Their results indicated that for film-forming coatings, thickness of the coating played a huge role as thicker coatings were more durable than thinner films. Semi-transparent dark coatings performed more efficiently than semi-transparent light coatings. Semi-transparent coatings required maintenance after 1 year. Checking and cracking was the main cause of coatings failure.

There was a lack of information about specific coatings used in this experiment for more profound analysis. However, in general it can be said that surface modified materials performed really well as they had higher colour stability than other materials.

4.2.6 Composites

Composites were represented with 6 specimens in this experiment. Composites such as fibreboard and particleboard coated with bamboo have not held their original colour firmly while other composites such as Tricoya and bio-ceramics have performed really well. Colour change of composite materials is illustrated in Figure 4.16.

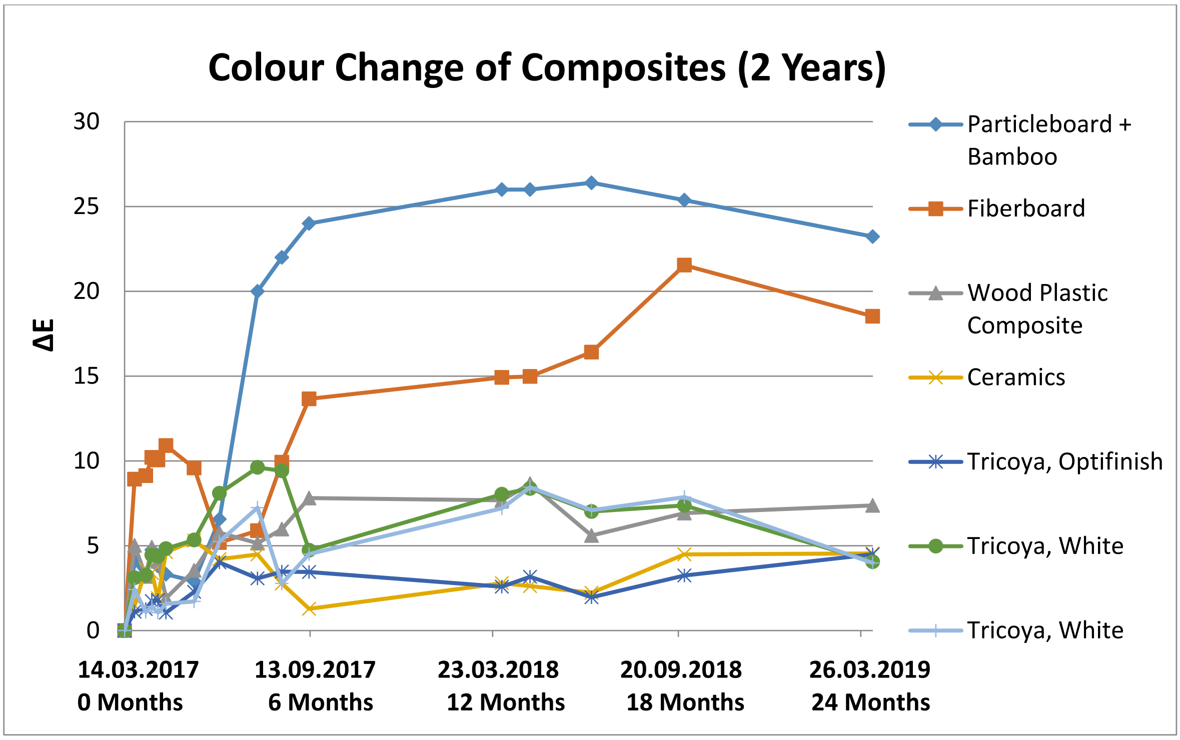

Figure 4.16. Colour change of composites

Tricoya samples held their colour really well. Rowell (2006) and Feist (1991) suggested that acetylated materials have great colour stability. However, as this thesis experiments have shown so far, simple acetylation could not maintain its original colour. Tricoya, however, is an acetylated MDF that has a coating, as well. This combination seems to improve colour stability as Tricoya samples in this experiment have been really colour stable.

Bamboo coated particleboard and fibreboard have changed their colour significantly. Reason behind the colour change of bamboo coated particleboard is its loss of coating after first months of exposure, therefore, colour change was inevitable and this specimen should be considered as disqualified. Figure 4.17 illustrates how bamboo coated particleboard lost its bamboo coating completely after sixth month of weathering and left particleboard exposed to the weather factors. Bamboo coating and particleboard did not have sufficient attachment between them, therefore, weather factors could remove the bamboo coating. It can be concluded that this combination with such attachment is not suitable for outdoor conditions.

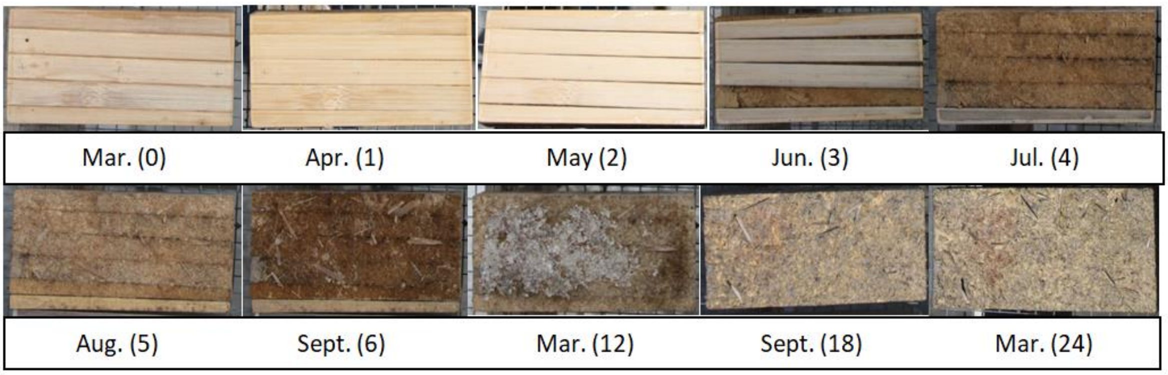

Figure 4.17. Visual appearance change of bamboo-coated particleboard (Legend: Calendar Month (Time of Exposure in Months))

In conclusion, Tricoya, bioceramics and wood-plastic composites showed great colour stability in these experiments. Bamboo coated particleboard and fibreboard proved that they are not suitable for outdoor conditions.

4.2.7 Hybrid Modification

Hybrid modification is the largest group with 25 materials. Hybrid modification consists of two modification methods. First modification in this experiment was mainly thermal or chemical and second modification was mainly coating or in some cases – impregnation. In general, hybrid modification managed to keep materials colour as 20 hybrid modification materials were below median average ΔE while 5 were above it. Colour was best held by coated Accoya materials and biofilm coated impregnated wood. By far the worst colour keeper (41 U/M) was pine that was treated with Nano TiO_2 + lineseed oil. Other hybrid modified materials that were not able to keep their colour too well, were: thermally modified + oiled spruce (25 U/M) and Madurit impregnated + thermally modified poplar (23 U/M). Colour change of all the hybrid modified materials can be seen in Figure 4.18.

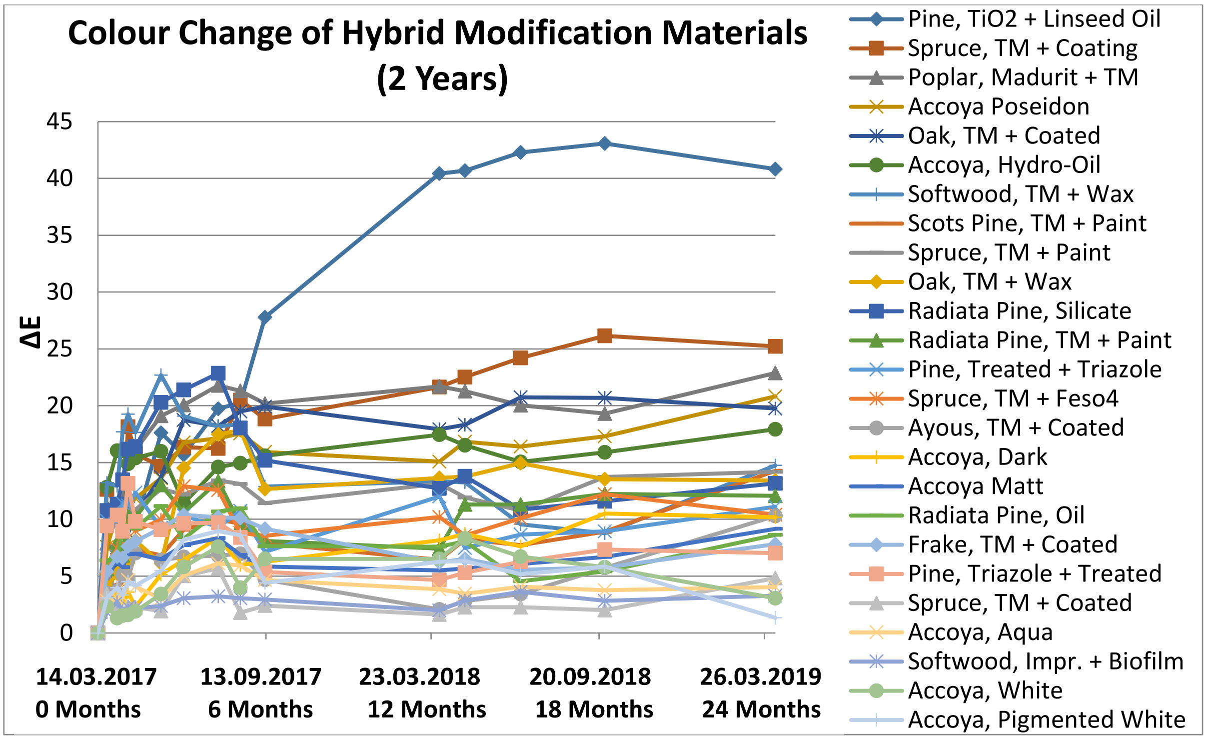

Figure 4.18. Colour change of hybrid modified materials

Hybrid modification tends to be so successful mainly because most of the hybrid modified materials include coating and from previous figures it can be seen that coatings have improved colour stability of the material. One material though, Nano TiO_2 + lineseed oil, was the worst performer of all the 120 materials as it changed its colour the most.

TiO_2 is a UV screener that should give colour stability to the material. Study of Ozgenc *et al* (2012) did a weathering test where TiO_2 was used. They concluded that UV screeners alone do not perform as well as when combined with other treatments. However, TiO_2 still gave good colour stability. Study of Shen *et al* (2018) also confirmed that TiO_2 improved colour stability of the wood. Ozgenc *et al* (2012) study noticed that TiO_2 did not penetrate as much on pine samples as on other (i.e. beech) samples. Sample used by the author of this thesis was a pine so it may be possible that TiO_2 did not have a sufficient penetration on this specimen, as well.

Problem of a bad colour performance cannot be put on lineseed oil also as Ozgenc *et al* (2013) study stated that lineseed oil improved colour stability of wood. Therefore, a collage was made (Figure 4.19) to see the colour changes more precisely. From collage it can be seen that TiO_2 and lineseed oiled treatments have, indeed, improved colour stability of the material as most of the materials under evaluation had turned greyish already after 6 months of weathering while this sample still had its yellowish colour. However, when this sample started to change its colour, changes were rapid and strong, causing the large movement in colour space coordinates. Changes may be caused by the colonisation of fungi as lineseed oil provides food for bio-organisms.

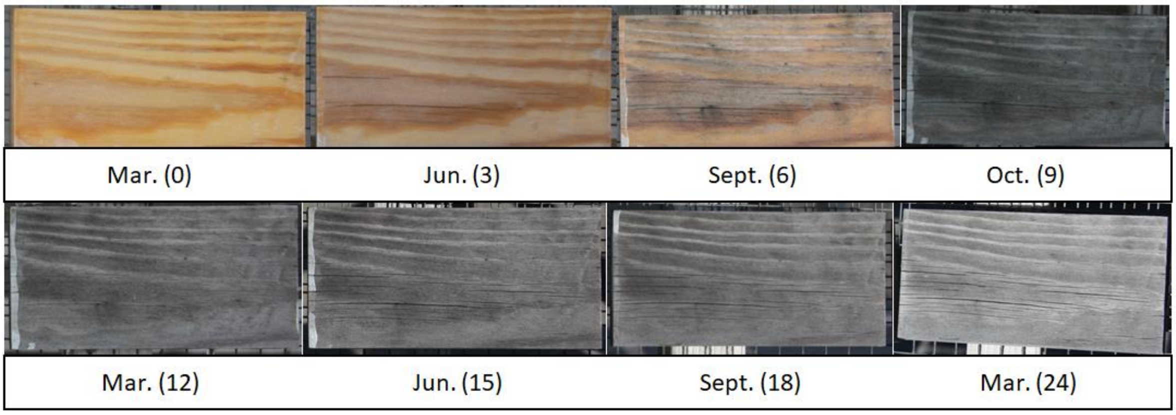

Figure 4.19. Colour change of TiO2 impregnated + lineseed oil treated material (Legend: Calendar Month (Time of Exposure in Months))

Less colour changed hybrid modified materials included many coated Accoya specimens. Accoya is an acetylated wood and acetylation improves colour stability of the wood (Schaller & Rogez, 2007; Temiz *et al*, 2007; Rowell, 2005). However, as studies of this thesis showed, simple acetylation did not improve colour stability of wood. Figure 4.20 and Figure 4.21 are proving that when coating is applied to acetylated wood, it improves colour stability significantly and they perform really well together. Figure 4.20 shows that white Accoya has held its colour very well. Reasons behind visual colour change fluctuations are caused by temporary weather conditions during picturing.

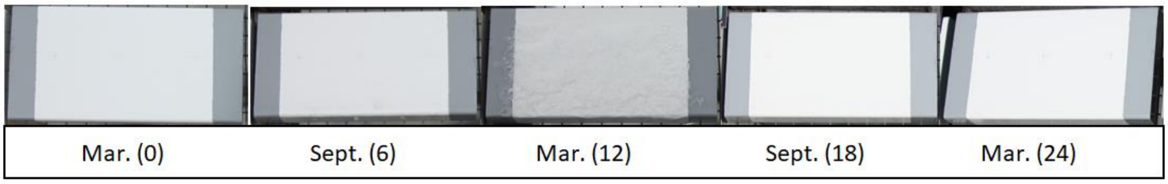

Figure 4.20. Visual colour change of Accoya (white) (Legend: Calendar Month (Time of Exposure in Months))

Figure 4.21 is an example of a matt Accoya that also proves the fact that acetylated + coated wood are performing really well in outdoor conditions as this is one of the best specimens regarding the colour change of a material.

Figure 4.21. Visual colour change of Accoya (matt) (Legend: Calendar Month (Time of Exposure in Months))

In general, hybrid modification has improved colour stability of the materials as majority of hybrid modified materials had lower colour changes than average materials.

4.2.8 Highest and Lowest Colour Changes

Specimens were ranked according to their colour change *ΔE* and 10 highest and lowest colour changers are presented in the following figures.

Figure 4.22 shows the biggest colour changed specimens. It consists mainly from natural and impregnated materials. The biggest colour changer was Nano TiO_2 impregnated + lineseed oil coated pine. Other impregnated materials that changed their colour the most are AATMOS, TA and Fluorosilane while natural spruce and pine were also one of the most colour changed specimens.

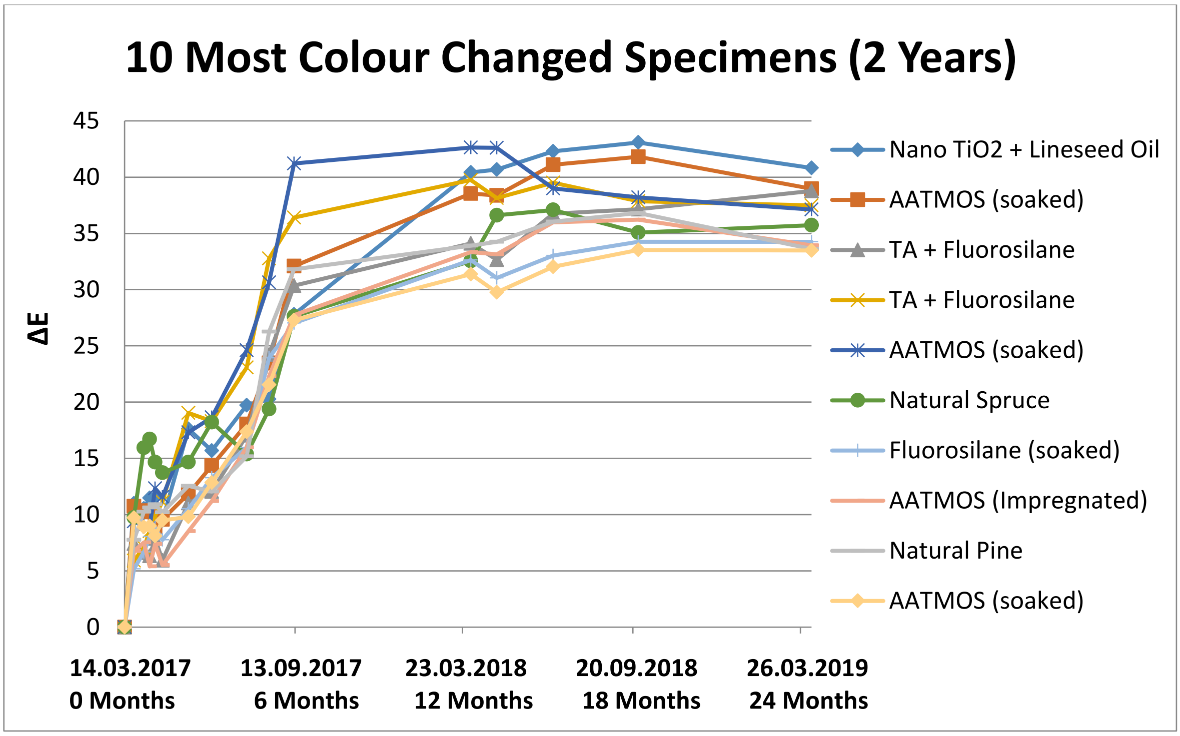

Figure 4.22. Ten most colour changed specimens

Figure 4.23 shows the 10 less colour changed materials. It consists mainly from coated and chemically modified materials. Smallest colour change was by Accoya that was coloured white. Other less colour changed samples were coated softwood, impregnated + biofilm coated softwood, thermally modified + coated spruce. It also included various Tricoya and other Accoya materials that were coated, as well. Ceramic material hs shown very good colour stability as it has stayed consistant during the whole 2 years of weathering.

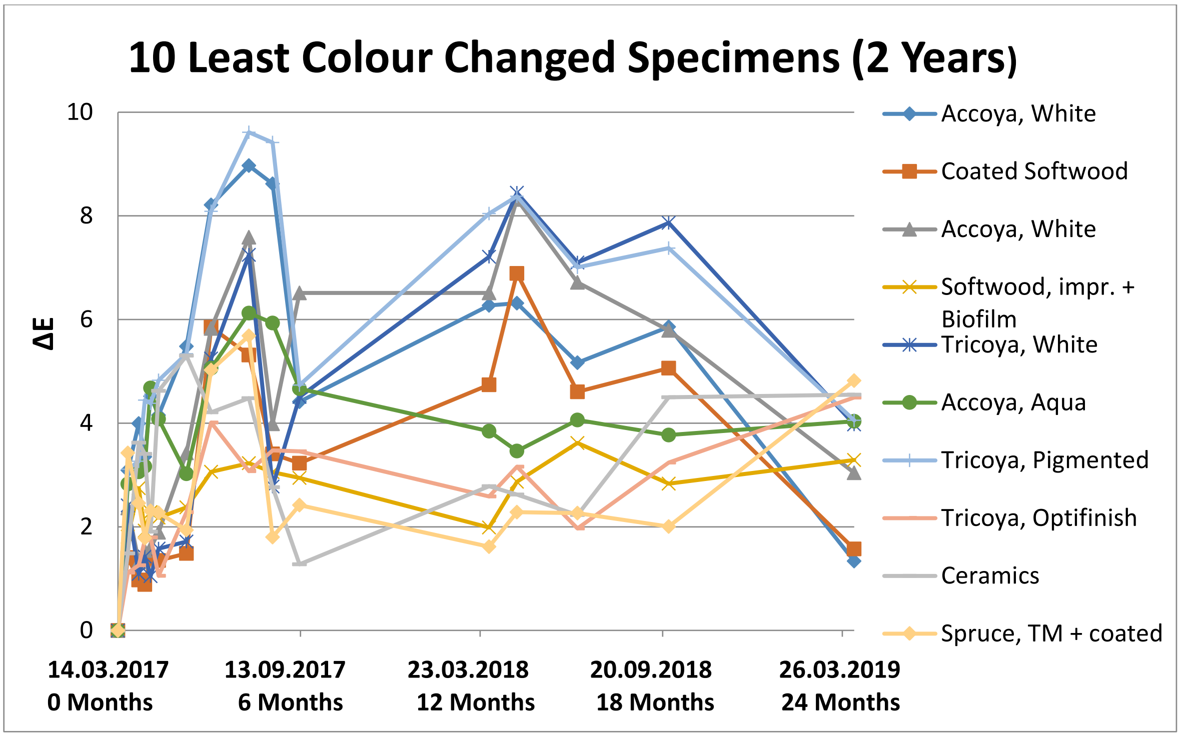

Figure 4.23. Ten least colour changed specimens

These results are confirming the trend that was seen from group analysis. In general it can be said that natural and impregnated materials have had the worst colour stability in this experiment. Thermally modified wood has had moderate colour stability. Surface modification, chemical modification and hybrid modification has mostly improved colour stability of wood.

4.3 Checks

Surface checks of materials were measured after every 3 months. Winter month (9 and 21) measurements were cancelled as weather conditions did not enable measurement taking. Checks were evaluated by quantity, total check length and mean maximum width.

When materials arrived to Estonia for experiments, only 21 materials had visible checks on them. After first 3 months of weathering, 19 new materials had checks so there were 40 materials in total that had checking of the surface. After 24 months of weathering, over half (63) of the materials had checks on them. This is illustrated in Figure 4.24. Amount of materials that have checks on them rose steadily after every 3 months but more rapid checking appeared during first months of measuring as microdefects might have opened more, therefore, enabling to see them visually. All winter period measurements (months 9 and 21) were cancelled as materials were under snow and ice or they were so wet that it was not possible to get adequate results.

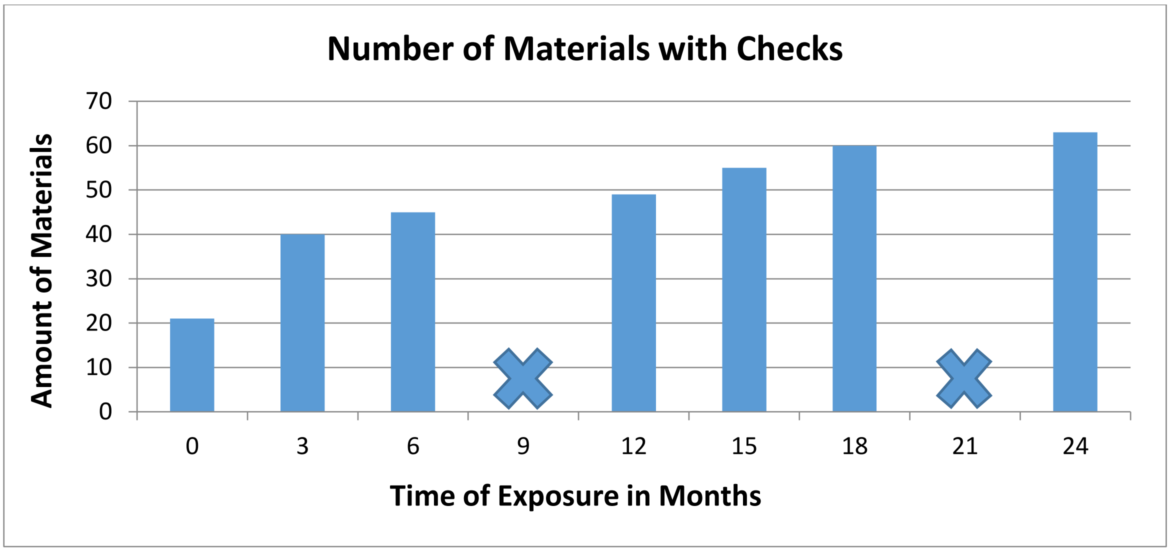

Figure 4.24. Number of materials with checks

Figure 4.25 illustrates how quantity and total length of the check rose during time. It shows that appearing of checks is relatively slow but firm process that is happening during time. Figure 4.25 is illustrating general checking of all the specimens and no precise specimens have been pointed out. Specimens with longest and widest checks are presented in later figures.

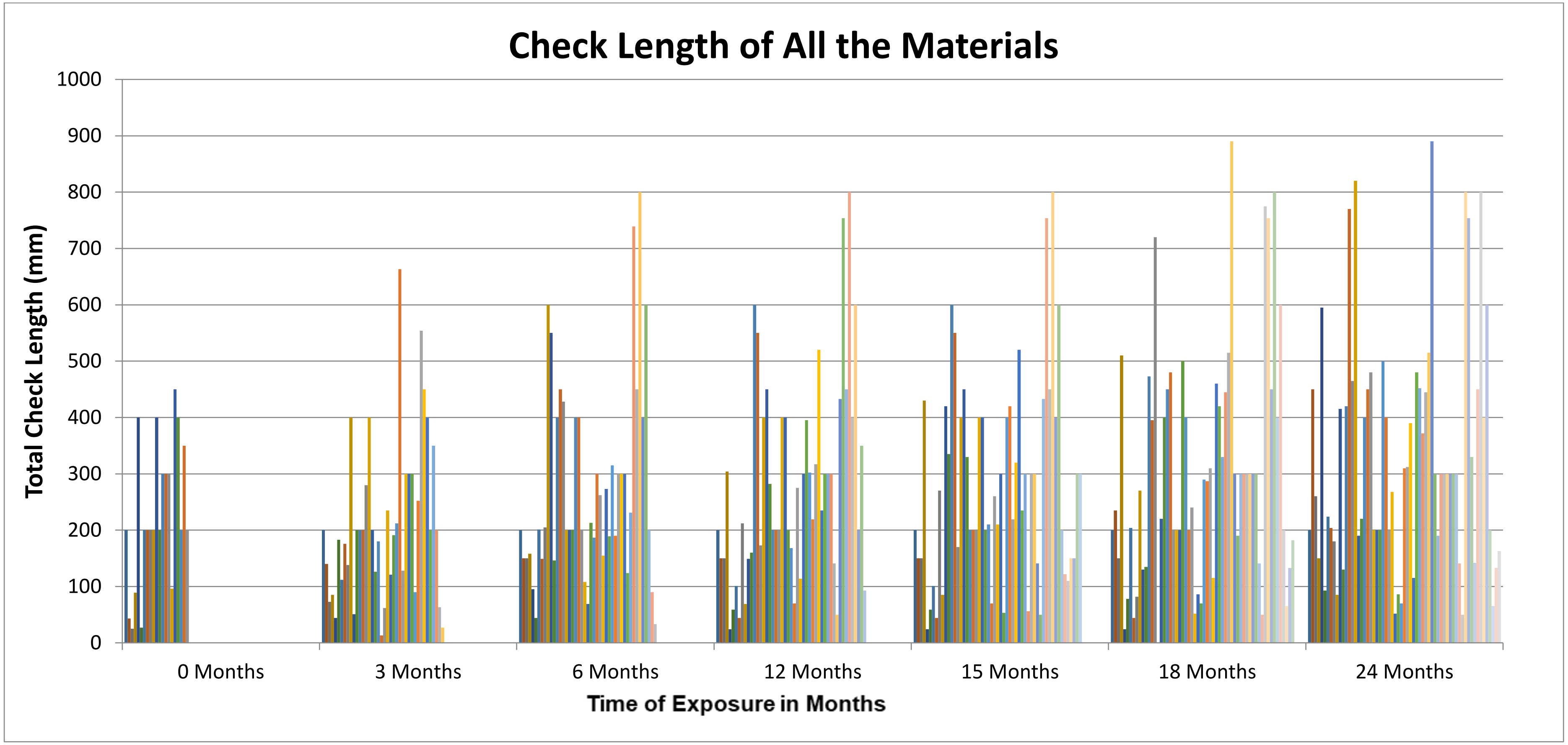

Figure 4.25. Check length of all the materials

Some materials had so many checks even before measurement taking that they are considered as uncountable checks and not considered in the total check length figure. Materials with uncountable checks include mainly materials that have structural checks such as oak and various tropical hardwoods. Materials with checks were listed (Appendix 2) and 15 materials that had biggest total countable check lengths are in Figure 4.26.

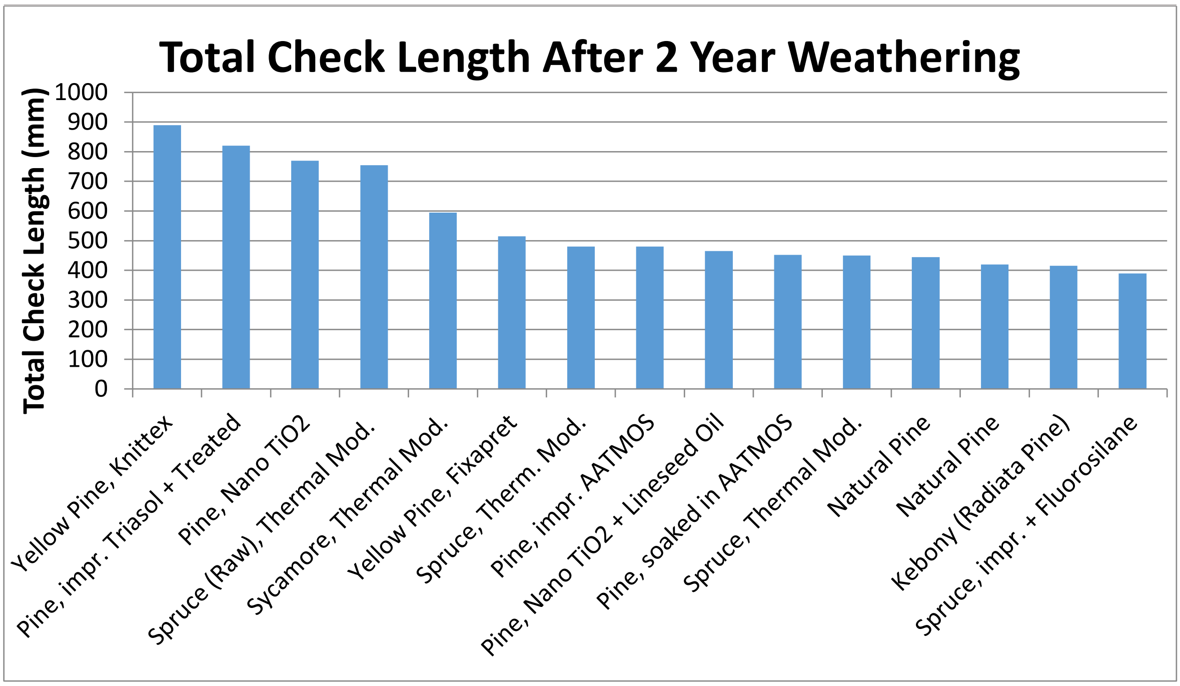

Figure 4.26. Fifteen materials with the longest total check length

List of the biggest total check length materials are mainly pine and spruce specimens that are natural, thermally modified or impregnated with some kind of preservative. Longest checking appeared on Knittex impregnated yellow pine as total length of checks was 890 mm, it is almost 7 times the length of a sample. Study of Sandberg *et al* (2017) stated that similar impregnation chemicals to Knittex are meant to improve dimensional stability and reduce water uptake of the wood, however, they are prone to checking. This statement got confirmed by this thesis experiments also as Knittex has the longest total check length and is prone to surface checking.

Just like in the highest colour changed materials figure, AATMOS and fluorosilane impregnated materials are present in Figure 4.26, as well. Aim of AATMOS and fluorosilane is to make wood resistant against decay, insects and water uptake (Donath *et al*, 2006). However, results show that they are not able to prevent checking of the wood as several AATMOS and fluorosilane samples are included in the longest total check length figure. Similar conlusions were made by Donath *et al* (2006) as they stated that silane treated materials did not show any reduction of surface checking.

Mean maximum width of the materials were measured and results are presented in Figure 4.27, where materials with wider than 1 mm checks are pointed out. Widest checks were on natural oak with 3 mm. Impregnated poplar, spruce and pine, natural spruce, pine and teak are other materials that have the widest checks. One thermally modified spruce is in the list, as well. Impregnated materials in the list are AATMOS, TA or Fluorosilane treated.

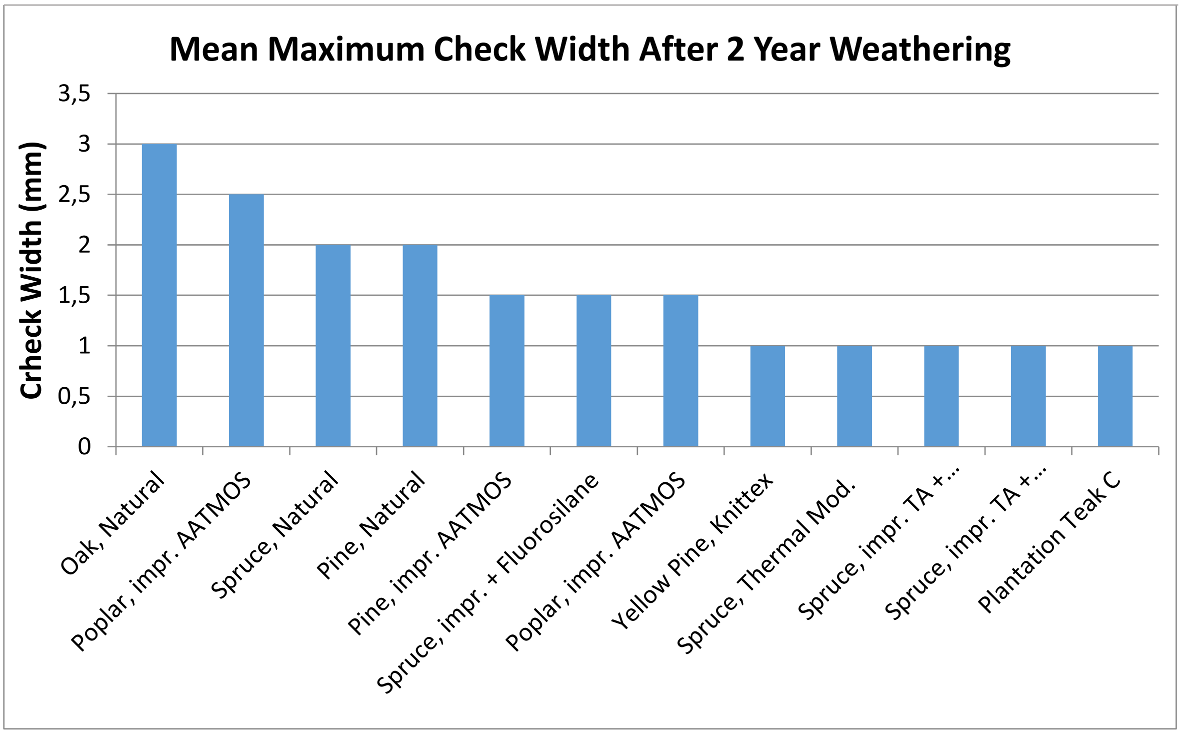

Figure 4.27. Materials with check length more than 0,99 mm

Materials that are dominating total check length figure are present in mean maximum check width figure, as well. Natural, thermally modified and impregnated materials are all present in both figures. There was a disagreement pointed out in literature overview where studies of Torvinen (2010) and Jämsa *et al* (2000) stated that thermally modified wood are prone to checking while studies of Truusa (2015) and Vernois (2001) stated that thermal modification has reduced surface checking of the wood. Author of this thesis rather agrees with Torvinen and Jämsa *et al* (2000) studies as results gathered during this experiment show that thermally modified wood is similarly prone to checking as unmodified wood.

Surface modified and composite materials showed the greatest improvement in checking as not a single composite material had checks on them. This is mainly because there was only 7 composite materials tested. However, they were all resistant to checking. Surface modification improved checking resistance of the materials significantly as only 5 surface modified materials out of 16 had visible checks on them.

It can be concluded that natural, thermally modified and impregnated materials had the longest and widest surface checks. Surface modified, hybrid modified and composite materials were the best for improving surface checking of the material. Chemically modified materials are moderately prone to surface checking.

CONCLUSIONS

The aim of this work was to evaluate weathering resistance of 120 bio-based materials in an Estonian climate. Weathering resistance was evaluated by the colour change and appearance of checks. Conclusions made from experiments are following:

1. Natural wood does not have a high colour stability but from natural wood, oak is one of the most colour durable species and spruce is one of the lowest.

2. Uncoated acetylated materials had a significant colour change already after 1 month of weathering. However, Furfurylated, Tricoya and Accoya wood showed great colour stability.

3. Surface modified materials held their colour well as 14 samples (out of 16) had lower colour changes than an average specimen during these tests. Hybrid modified materials were also one of the most colour stable materials as 20 samples (out of 25) changed their colour less than an average specimen.

4. Impregnated materials showed the worst colour stability as 25 materials (out of 28) changed their colour more than an average specimen.

5. Colour change of thermally modified materials was moderate as they changed less colour than unmodified materials but more colour than surface modified materials.

6. Surface checking of the wood happened slowly and firmly during time. Before weathering, 21 materials had checks on them but after 2 years of weathering, over half of the materials (63 out of 120) had appearance of checks.

7. Longest checking appeared on Knittex impregnated yellow pine as total length of checks was 890 mm. Widest checks were on natural oak (3 mm). Natural, impregnated, and thermally modified materials were other samples that had the longest and widest checks.

8. There was a disagreement in studies whether thermally modified is prone to surface checking or not. Results gathered during this thesis show that thermally modified wood is similarly prone to checking as unmodified wood.

During this thesis, important conclusions were made regarding the weathering resistance of bio-based facade materials. However, as the experiments included large amount of materials, mostly general analysis could be made.

SUMMARY

Weathering tests in this Master Thesis were done in collaboration with the BIO4ever project. BIO4ever is an international project that has a goal of raising awareness about the benefits of using bio-based materials in a construction sector. The practical outcome of this project is a software that simulates appearance change of bio-based facade materials in outdoor conditions.

The author of this thesis contributed to the project by evaluating changes in material appearances during 2 years of outdoor exposure. The aim of this work was to evaluate weathering resistance of 120 bio-based materials in an Estonian climate.

Materials were evaluated by the colour change and checks. 120 materials were under evaluation and they were divided into 7 groups: natural, thermal modification, chemical modification, impregnation, composites, surface modification, and hybrid modification.

Natural and impregnated materials showed the worst colour stability while surface, chemical and hybrid modification mainly improved colour stability of the materials. Thermally modified materials had moderate colour stability.

Natural, thermally modified and impregnated materials had the longest and widest surface checks. There was a disagreement in the literature overview, whether thermally modified wood is prone to checking or not. Results of this experiment showed no improvement of checking resistance for thermally modified wood. Surface modified and composite materials were the best for improving surface checking resistance of the material. Chemically modified materials were moderately prone to surface checking.

During this thesis, important conclusions were made regarding the weathering resistance of bio-based facade materials. Experiments included large amount of materials, therefore, analyses were done mostly by the material groups instead of individual analyses of the materials. This study creates opportunities for future researches to make more profound analyses about specific groups or treating methods as various interesting analyses could be made that did not fit into the content of this thesis.

KOKKUVÕTE

Antud magistritöö on teostatud BIO4ever porjekti raames. BIO4ever on rahvusvaheline projekt, mille eesmärgiks on tõsta teadlikust puidupõhiste materjalide kasutamise eelistest ehitussektoris. Projekti praktiliseks eesmärgiks on välja arendada tarkvara, mille abil on võimalik visualiseerida aja jooksul tekkivat materjalide muutust välistinigmisutes.

Magistritöö autor panustas BIO4ever projekti arengusse mõõtes materjalide värvusemuutust ja pragude teket Eesti kliimas. Magistritöö eesmärgiks oli mõõta puidupõhiste fassaadimaterjalide vastupidavust Eesti kliimas.

Materjalide muutust väliskeskkonnas hinnati värvusemuutuse ja pragude tekke järgi. Testimisel oli 120 erinevalt töödeldud katsekeha, mis jaotati töötlusviisi alusel seitsmesse kategooriasse: naturaalne, termiliselt modifitseeritud, keemiliselt modifitseeritud, immutatud, komposiidid, pealispinnalt modifitseeritud ja hübriid-modifitseeritud katsekehad.

Naturaalsed ja immutatud materjalid olid kõige halvema värvuse vastupidavusega ehk nad muutsid kõige rohkem värvust. Pealispinnalt, keemiliselt ja hübriidselt modifitseeritud materjalid näitasid üles kõige paremat värvuse püsivust. Termiliselt modifitseeritud katsekehade värvipüsivus oli keskmine.

Kõige altimad materjalid pragunemisele olid naturaalsed, termiliselt modifitseeritud ja immutatud matejalid. Kirjanduse ülevaates oli ebakõla mitmete allikate vahel, kas termiliselt modifitseeritud katsekehad on altid pragunemisele või mitte. Antud töö tulemused näitasid, et termiliselt modifitseeritud katsekehad ei olnud suurema vastupidavusega pragude tekkele kui naturaalsed katsekehad. Pealispinnalt töödeldud, hübriidmodifitseeritud ja komposiitmaterjalid olid pragude tekkimise vältimisel kõige efektiivsemad. Keemiliselt modifitseeritud katsekehad pragunesid keskmise mõõdukusega.

Magistritöö käigus tehti olulisi järeldusi seoses puidupõhiste fassaadiamterjalide vastupidavusega väliskeskkonnas. Katsed hõlmasid väga palju erinevaid materjale, seega keskenduti antud töös rohkem tulemuste analüüsile materjalide gruppide kaupa, mitte iga katsekeha individuaalsele analüüsile. See jätab võimaluse edasiseks teadustööks valida välja mõni spetsiifilisem materjalide grupp või materjal ja uurida ühte valdkonna põhjalikumalt. Võimalusi antud töösse mitte mahtunud spetsiifliste võrdluste tegemiseks on tohutult. Töö käigus tehtud katsed olid õnnestunud ja põhjalikud järeldused said tehtud.

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Appendix 1

Appendix 1. Colour change of all the materials after 2 years of weathering

Sample Description	Specimen nr	Type	ΔE After 2 Years	Standard Deviation
Pine, Nano TiO2 + Linseed Oil	37	Hyb	40,8	2,2
Spruce, AATMOS soaked	63	Impr	39,0	1,3
Spruce, TA Impr. + Fluorosilane	65	Impr	38,8	4,0
Poplar, TA Impr. + Fluorosilane	58	Impr	37,5	3,1
Poplar Soaked AATMOS	57	Impr	37,1	0,8
Natural Spruce	102	Nat	35,7	1,7
Spruce, Fluorosilane soaked	67	Impr	34,2	1,6
Spruce, Impr. AATMOS	62	Impr	33,9	1,6
Pine	34	Nat	33,6	3,7
Pine, Soaked AATMOS	72	Impr	33,5	1,9
Pine Impregnated + Soaking in Fluorosilane	73	Impr	32,6	1,7
Poplar, Impregnated AATMOS	56	Impr	32,2	3,4
Pine, Impregnated AATMOS	71	Impr	31,6	4,6
Pine	74	Nat	31,3	4,6
Larch With Laser Graver	120	Nat	31,0	2,9
Southern Yellow Pine	81	Nat	30,7	3,4
Natural Pine	7	Nat	30,4	2,8
Spruce, Fluorosilane	66	Impr	30,0	1,5
Silver Fir	22	Nat	30,0	1,4
Beech, Silicone	17	Impr	29,8	3,9
Poplar, TA Impregnated + Fluorosilane	59	Impr	29,6	2,5
Softwood	90	Nat	29,0	1,5
Poplar, Fluorosilane	60	Impr	28,6	1,7
Spruce, TA + Fluorosilane	64	Impr	28,6	2,7
Plantation Teak	93	Nat	28,6	2,3
Poplar, Impr. + Soaking in Fluorosilane	61	Impr	28,5	1,4
Pine, DMDHEU	82	Impr	27,8	1,6
Pine, nanocoated	112	Sur	27,4	1,2
Plantation Teak	95	Nat	26,9	2,0
Frake, TM	46	Term	25,4	2,2
Spruce, TM + Oil	105	Hyb	25,2	1,9
Fixapret	75	Impr	25,0	3,2
Plantation Teak	94	Nat	24,2	0,7
Pine, TiO2	36	Impr	24,2	0,2
Radiata Pine, TM	45	Term	24,2	1,9
Pine, TM	28	Term	23,8	3,1
Silver Fir	25	Impr	23,4	4,2
Particleboard and Bamboo	40	Com	23,2	1,4

Sample Description	Specimen nr	Type	ΔE After 2 Years	Standard Deviation
Süruce, Tm	103	Term	23,1	1,2
Poplar, Madurit + TM	80	Hyb	22,9	1,8
Natural Oak, Waxed	108	Sur	22,9	0,6
Spruce, TM	47	Term	22,0	1,4
Spruce, TM	26	Term	21,9	2,6
Plantation Teak	96	Nat	21,8	3,7
Silver Fir, treated	23	Impr	21,5	0,9
Accoya Poseidon	83	Hyb	20,8	3,0
Natural Oak	110	Nat	20,8	4,1
Beech, impr.	18	Impr	20,7	3,1
Silver Fir	24	Impr	20,5	1,6
Madurit	79	Impr	20,3	3,1
Poplar, TM	14	Term	20,0	1,1
TM Oak + Coated	107	Hyb	19,7	5,6
Beech, PBS	21	Impr	19,6	1,7
Natural Beech	43	Nat	19,4	2,9
Ayous, TM	54	Term	19,3	1,8
Frake, TM	53	Term	19,2	1,7
Bamboo Cladding	13	Nat	18,9	4,7
Pine Thermo D 212 ˚C	8	Term	18,7	2,1
Spruce Thermo D 212 ˚C	5	Term	18,6	4,9
Beech	20	Nat	18,5	2,7
Fiberboard	41	Com	18,5	5,3
Larch Lightly Burned	115	Sur	18,4	4,2
Knittex	76	Impr	18,3	0,2
Accoya, Hydro-Oil	1	Hyb	17,9	1,4
Pine, Aqua Coating	118	Sur	17,9	2,4
Natural Oak Coated	106	Sur	17,4	3,7
Sycamore, TM	16	Term	17,4	1,4
Pine, TM	35	Term	17,0	0,4
Poplar, TM	78	Term	16,7	2,3
Accetylated Radiata Pine	51	Chem	16,5	1,3
Acetylated Alder	49	Chem	16,4	0,8
Thermally Treated Obeche	48	Term	15,4	2,3
Bamboo Decking	12	Nat	15,3	0,8
Pine, OHT	33	Term	14,8	2,2
Softwood, TM + Wax	88	Hyb	14,8	1,6
Poplar	77	Nat	14,6	1,6
Acetylated Beech	50	Chem	14,3	1,0
Pine, TM + Coating	29	Hyb	14,3	4,0
Spruce, TM + Coating	27	Hyb	14,2	2,3
White Treatment Solas	42	Sur	14,0	0,2
Natural Ceris Oak	44	Nat	13,8	2,2

Sample Description	Specimen nr	Type	ΔE After 2 Years	Standard Deviation
Ash Thermally Treated	15	Term	13,5	2,6
Oak, TM + Wax	109	Hyb	13,4	0,5
Radiata Pine, Silicate	10	Hyb	13,2	2,5
Thermally Modified Oak	111	Term	12,6	0,2
Kebony	31	Chem	12,4	1,1
Softwood, Coated	69	Sur	12,1	2,6
Radiate Pine, TM + Coating	30	Hyb	12,1	0,8
Softwood, TM	89	Term	12,0	1,3
Beech, PLA	19	Impr	11,3	0,9
Pine, Treated + Triazole	39	Hyb	11,1	1,6
Spruce TM + FeSo4	6	Hyb	10,4	1,8
Ayous TM + Coating	55	Hyb	10,3	0,8
Accoya, Dark	99	Hyb	10,2	0,7
Softwood, CEA impr.	91	Impr	10,1	1,7
Pine, Grey Coating	116	Sur	9,3	1,4
Pine, White Coating	117	Sur	9,3	2,6
Natural Spruce, Oiled	104	Sur	9,3	0,5
Accoya Matt	84	Hyb	9,2	3,8
Hardwood, for Windows	68	Sur	9,1	1,2
Larch Carbonized	114	Sur	8,8	4,0
Radiata Pine, Water	9	Hyb	8,6	0,5
Softwood, Water Base	86	Sur	8,5	1,7
Softwood, Solvent Base	87	Sur	7,9	0,3
Frake, TM + Coating	52	Hyb	7,8	0,8
Wood Plastic Composite	113	Com	7,4	1,2
TM Spruce, Over treated	119	Term	7,1	1,8
Pine, Triazole + Treated	38	Hyb	7,0	4,0
Scots Pine Kebony	32	Chem	6,8	3,4
Spruce, Coated	100	Sur	5,5	0,7
TM Spruce, Coated	101	Hyb	4,8	1,0
Bio-Ceramics	11	Com	4,5	1,0
Tricoya, Optifinish	85	Com	4,5	0,3
Tricoya, White	4	Com	4,1	1,0
Accoya, Aqua	2	Hyb	4,0	0,9
Tricoya, White	97	Com	4,0	1,5
Softwood, Biofilm	92	Hyb	3,3	0,4
Accoya ,White	98	Hyb	3,0	0,2
Softwood, for Windows	70	Sur	1,6	0,3
Accoya, White	3	Hyb	1,3	0,3

Appendix 2

Appendix 2. Checks of all the materials after 2 years of weathering (symbol "+" means estimated and uncountable)

26.03.2019	Material	Specimen Number	Number of Cracks	Total Crack Length	Mean Maximum Crack Width	Treatment Type
24 MONTHS	Accoya + hydro-oil	1	20	200	0,1	Hyb
	Spruce, Thermal Mod.	5	3	450	0,1	Term
	Spruce, Thermal Mod.	6	4	260	0,9	Hyb
	Natural Pine (heartwood)	7	1	150	0,4	Nat
	Sycamore, Thermal Mod.	16	29	595	0,7	Term
	Beech impr. (Silicon)	17	23	93	0,1	Impr
	Beech impr. (PLA)	19	19	224	0,5	Impr
	Spruce, Thermal Mod.	26	32	204	0,4	Term
	Natural Scots Pine	28	12	180	0,2	Term
	Pine, TM + Coating	29	3	85	0,4	Hyb
	Kebony (Radiata Pine)	31	37	415	0,5	Chem
	Kebony (Scots Pine)	32	20+	130	0,15	Chem
	Natural Pine	34	9	420	0,25	Nat
	Pine, Nano TiO_2	36	39	770	0,7	Impr

Material	Specimen Number	Number of Cracks	Total Crack Length	Mean Maximum Crack Width	Treatment Type
Pine, Nano TiO2 + Lineseed Oil	37	33	465	0,5	Hyb
Pine, Impr. Triasol + Processed	38	12	820	0,4	Hyb
Pine, Processed + Impr. Triasol	39	22	190	0,7	Hyb
Oak, Natural	44	5	220	3	Nat
Pine TM	45	20+	400+	0,15	Term
Frake TM	46	20+	450+	0,75	Term
Spruce TM	47	20+	480	0,5	Term
Obeche TM	48	20+	200+	0,15	Term
Pine, Acetylated	51	20+	200+	0,15	Chem
Frake, TM + Coating	52	20+	200+	0,55	Hyb
Frake, TM	53	20+	500+	0,7	Term
Ayous TM	54	20+	400+	0,15	Term
Ayous, TM + Coating	55	20+	200+	0,15	Hyb
Poplar, impr. AATMOS	56	17	268	2,5	Impr
Poplar, impr. AATMOS	59	6	52	1,5	Impr
Sprcuce, impr. AATMOS	62	19	86	0,15	Impr
Spruce, Soaked in AATMOS	63	3	70	0,25	Impr
Spruce, impr. TA + Fluorosilane soaked	64	24	310	1	Impr

Material	Specimen Number	Number of Cracks	Total Crack Length	Mean Maximum Crack Width	Treatment Type
Spruce, impr. TA + Fluorosilane soaked	65	30+	312	1	Impr
Spruce, impr. + Fluorosilane soaked	66	27	390	1,5	Impr
Spruce, soaked in Fluorosilane	67	11	115	0,9	Impr
Pine, impr. AATMOS	71	32	480	1,5	Impr
Pine, soaked in AATMOS	72	35	452	0,9	Impr
Pine, impr + soaked in Fluorosilane	73	27	372	0,8	Impr
Natural Pine	74	27	445	2	Nat
Yellow Pine, Fixapret	75	26	515	0,5	Impr
Yellow Pine, Knittex	76	21	890	1	Impr
Yellow Pine, Natural	81	20+	300+	0,4	Nat
Softwood, impr.	86	29	190	0,75	Sur
Softwood, TM + Wax	88	2	300	0,15	Hyb
Softwood, TM	89	2	300	0,2	Term
Natural Softwood	90	2	300	0,15	Nat
Softwood, CEA impr.	91	2	300	0,2	Impr
Plantation Teak	93	20+	300+	0,2	Nat
Plantation Teak A	94	20+	300+	0,2	Nat

Material	Specimen Number	Number of Cracks	Total Crack Length	Mean Maximum Crack Width	Treatment Type
Plantation Teak B	95	4	141	0,65	Nat
Plantation Teak C	96	2	50	1	Nat
Spruce, Natural	102	20+	800+	2	Nat
Spruce (Raw), Thermal Mod.	103	15	754	1	Term
Spruce, TM + Oil	105	11	330	0,55	Hyb
Oak, TM + Coated	107	19	142	0,55	Hyb
Oak, Waxed	108	20+	450+	0,85	Sur
Oak, TM + Wax.	109	20+	800+	0,85	Hyb
Oak, Natural	110	20+	400+	0,9	Nat
Oak, Thermal Mod.	111	20+	600+	0,75	Term
Pine, Nanocoated	112	20+	200+	0,15	Sur
Pine, Syntilor Grey	116	7	65	0,3	Sur
Pine, Syntilor White	117	11	133	0,45	Sur
Larch, Natural	120	15	163	0,35	Nat