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PROPERTIES OF A NEW THERMOPLASTIC PLYWOOD PRODUCT

Master's thesis for the degree of Master of Science in Technology submitted for inspection, Espoo, 18th November 2013.

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Tiivistelmä

Ympäristöystävälliset arvot ovat lisääntymässä, mikä lisää puumateriaalin kiinnostusta. Samalla se luo myös paineita puutuotealalle kehittää tuotteita yhä pidemmälle ja ennen kaikkea jalostaa niitän siten, että puun negatiiviset puolet olisivat mahdollisimman huomaamattomia.
Tämän tutkimuksen perusteella Grada on uusi, innovatiivinen ja kiehtova tuote sekä tervetullut puutuoteteollisuuteen. Tutkimuksen tarkoitus oli ymmärtää paremmin termoplastisella liimalla valmistettua koivuvaneria tutkimalla sen muotopysyvyyttä, kosteudenkestoa sekä lujuusominaisuuksia lukuisien eri testien avulla. Koestukset tehtiin Gradalle kahdessa eri vaiheessa: ennen ja jälkeen muotoilemisen. Verrannaiskappaleina olivat perinteinen ureaformaldehydi-liimattu tasainen koivuvaneri sekä samaisella liimalla liimattu muotoiltu pyökkivaneri. Kosteudenkestävyyttä tutkittiin muotopysyvyyden rinnalla. Lujuusominaisuuksia puolestaan tarkasteltiin niin staattisten kuin dynaamisten testien avulla.

Testit osoittivat, että Grada kestää paremmin kosteutta, erityisesti ennen muotoilemista. Muotoiltu Grada kesti kosteusvaihteluita hieman huonommin. Tutkimuksessa löydettiin myös viitteitä mikroskooppisista halkeamista sekä sisäisistä jännitteistä, jotka todennäköisesti olivat aiheutuneet muotoilusta. Grada osoittautui jossain määrin alttiimmaksi olosuhdemuutoksille lyhyemmällä aikavälillä, mikä johtui mitä todennäköisimmin kuivemmista pintaviiluista.

Lujuustestit paljastivat mielenkiintoisia ilmiöitä. Arvot, joita Grada sai, eivät olleet korkeampia kuin perinteisen vanerin. Sen sijaan ne olivat huomattavasti tasaisempia, hajonta oli lähes huomaamaton, yhtä poikkeusta lukuun ottamatta. Vaikutti siltä kuin uusi liimakalvo olisi himmentänyt puun virheiden vaikutusta, muodostaen tasalaatuisen komposiitin upealla vanerin ilmeellä.

Tämän tutkimuksen testit suoritettiin vähäisillä koekappalemäärillä. Näin ollen on suositeltavaa tehdä testit uudestaan suuremmalla koekappalemäärällä, mikäli halutaan varmasti tieteellisesti luotettavat tulokset.

Avainsanat Vaneri, termoplastinen, ominaisuudet, muotopysyvyys, kosteuskestävyys, lujuusominaisuudet

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Abstract

Environmental aspects are more and more appreciated, which in one hand amplifies the attraction of wood products and in the other hand pushes the wood industry to develop more refined products to reduce the flaws of wood material. Grada appeared to be a new, innovative and intriguing product in wood industry. The aim of this study was to better understand the behaviour of the thermoplastic bonded plywood product by investigating its stability and strength properties through several distinctive tests. Tests were conducted to Grada in both stages, prior and after the forming process, with a comparison of the conventional products: urea formaldehyde bonded flat birch plywood and formed beech plywood. The moisture penetration through faces and edges was studied, in line with the dimensional changes. Furthermore, the strength properties of Grada were analysed through both static and impact tests.

Grada proved to have improved moisture resistance especially in the flat stage, before forming. The formed Grada seemed to have slightly lower MC resistance. There were also indications of tensions and microscopic cracks in the product, induced by the forming process. Grada also appeared to be more reactive to the surrounding conditions, but solely in short-term, which was mainly due to its lower moisture content.

The strength test showed interesting outcomes as well. Even though Grada did not attain higher strength values than the conventional plywood, there was seemingly less divergence among the values compared with the conventional plywood. The thermoplastic acted as a fader of the defects of wood, forging a uniform wood composite with the appearance of beautiful plywood.

The amount of test specimens was low, due to the variety of the tests. Thus, to scientifically prove the validity of the results, it is recommended to repeat the test with higher amount of specimens.

Keywords Plywood, thermoplastic, properties, stability, moisture resistance, strength properties

FOREWORD

It was really intriguing to do Master’s Thesis of something as interesting as Grada, which is new and innovative material in plywood industry! Therefore I want to thank UPM for giving me such an opportunity. Juhana Liimatainen and Mark Hughes, thank you for supervising the entire project and helping me when I had any questions or doubts – and for being always so excited, it was a great pleasure to work with you.

I also want to thank my mainstay, beloved life companion, Juha for all your support during this period. You were amazing! Patient, helpful, supporting, loving, … Words cannot describe how much all that meant to me ♥

And my sister Anne, my second mainstay, my personal trainer, Thank you for encouraging me and setting targets when needed, and being patient time to time. I love you from all my heart, thank you! Mum and Dad, Emma and Risto, thank you for supporting me for so many years and in so many ways!!! I’m also grateful for you that you let me wear the Teekkarilakki when I did not even walk yet – it was the beginning of this story ;)

There were many persons involved in this project – I’ll never forget you and the help you gave, thank you.

CONTENTS

TERMS

FB	Formed Beech
FG	Formed Grada
G	Grada
HEMA	Hydroxyethylene Methacrylate
J	Joule
LLDPE	Linear low-density polyethylene
MAPE	Maleated Polyethylene
MAPP	Maleic Polypropylene
MC	Moisture Content
MMA	Methyl methacrylate
MOE	Modulus of Elasticity
MOR	Modulus of Rupture
PF	Phenol formaldehyde
Thermoplastic	Material that becomes soft while heating it and solid when it is cooled down. It can be repeatedly reheated and reshaped without damages [Oxford English Dictionary Webpage]
Thermoset	Something that cannot be melted by warming it [Oxford English Dictionary Webpage]
UF	Urea-formaldehyde bonded plywood, i.e. conventional plywood, comparable product for formable Grada
UFG	Unsanded Formed Grada
WPC	Wood Plastic/Polymer Composite

1 INTRODUCTION

UPM-Kymmene Wood Oy (“UPM”) manufactures, amongst other products, plywood and wood plastic composites. During 2011 UPM launched a somewhat radical new product, which is likely to have an interesting impact on the plywood industry. The new product consists of veneers, as in normal plywood, but when it comes to bonding, the traditional thermosetting urea formaldehyde (UF) and phenol formaldehyde (PF) resins are replaced by thermoplastic films that form a chemical bond with the wood surface. In the plywood industry there had been interest towards a solid glue-line for several years, but no successful product or technology attempt had been introduced. Now UPM has been able to develop a solid glue-line, without formaldehyde, which is considered a risk factor for health, especially for the ones who are involved in the manufacturing process. The first two mentioned properties are not however the revolutionary factors for the success. The property that has evoked perhaps the most interest in audience has been the possibility of post forming the material, as well as the effect of a more composite like product. As a consequence of the thermoplastic nature of the film, the fabricated boards may then be re-formed (by heating) after the initial manufacturing process, and moulded into 3 dimensional forms. This opens up a vast array of new application possibilities, such as furniture and other products that benefit from curved sections. Although a significant volume of research that has already been carried out by UPM, it has been observed that this new product appears to have various unexpected features that customers may well be prepared to pay more for. These include: improved stability, improved strength and differences in the susceptibility of the material to biological degradation. In short, the new material may be thought of not necessarily as replacement plywood, but a new composite material class. However, in order to market these new features, it is important to adequately quantify these improvements in stability, strength and resistance to bio-deterioration.

The aim of this study was therefore to better understand the reasons behind the phenomena leading to better strength and stability in this new product and to obtain quantitative data to enable the product to be marketed better. Therefore, a series of experiments were conducted that focused on understanding better the stability and strength properties of the product in two conditions – i) as the manufactured product before post-forming and also ii) the post manufacture formed product (i.e. a representative 3-D structure). The reason for this approach was that it is likely that during the post forming (moulding) process, structural changes, (for example the development of internal stresses) occur that give the “formed” product different characteristics to the manufactured flat panels. In addition, the results were compared with conventional UF bonded plywood in both stages: flat and formed.

Grada material:
The new bonding film used in Grada is ready-made in a controlled environment, thus it can be presumed to be more uniform than the UF resin, which is mixed on site. The solid glue-line does not increase the MC of the veneers, in contrast to conventional plywood

manufacturing. This can be presumed to reduce the inner stresses of the veneers that the successive drying and absorption may cause. The uniformity of the glue-line and the lack of liquid in the bonding may also reduce the development of steam pockets if the veneers are dry enough. The plies in Grada are identical to the plies used in conventional birch plywood. The sole differentiating factor is the adhesive used, and the MC of the plies since the adhesive requires less moisture to adequately bond the plies. One clear and definitive advantage of the bond-line used in Grada is its non-toxicity; it contains no formaldehyde. Several studies have shown the danger of this widely used ingredient [OECD SIDS 2002]. In addition, the formaldehyde of the conventional plywood resin spreads easily in the manufacturing conditions, in the hot and liquid stage; thus there are apparent health risks for the workers.

The traditional process to manufacture formed plywood includes several stages. In the furniture industry for example, the manufacturing of the formed plywood starts with cutting the veneers in the desired dimensions, then grading them as in conventional plywood manufacturing process. In the third, the liquid glue is mixed and applied to the plies. Then plies are laid up and pressed together. Grada reduces all the untidy phases of the process. The board needs only to be heated up to 130 °C (at the core of the board) and formed into the desired form. This requires much less investments and time. An animation of the manufacturing process of traditional formed plywood and formed Grada can be seen through the following link:

https://www.youtube.com/watch?v=UnM-gddpriM

In addition Grada enables partial forming, which can be easily seen from the Figure below. The Kaava-chair by Isku is made from only one piece of plywood, and it is bent in many directions.

Figure 1 Isku's Kaava-chair, made from only one piece of Grada. In red can be seen the parts, where it has been formed [Laakkonen]

2 LITERATURE REVIEW

In the literature review the objective was to gather information about other similar products and their behaviour to be able to better evaluate the influence of different variables. The focus of this review was on the stability of the product.

2.1 Wood material

Wood has been used in buildings and different other products for ages. During the last decades, other materials dominated e.g. building markets, but now the situation is about to change, at least there are several attempts and signs for that; however, in the building industry the change is not easy. The roots of concrete and steel industry, for instance, are deep and to turn people's prejudices into attraction takes time. However, environmental consciousness has arisen and people are seeking more and more environmentally friendly products. In the graph below can be seen the interest of Green Building programs in the U.S. cities.

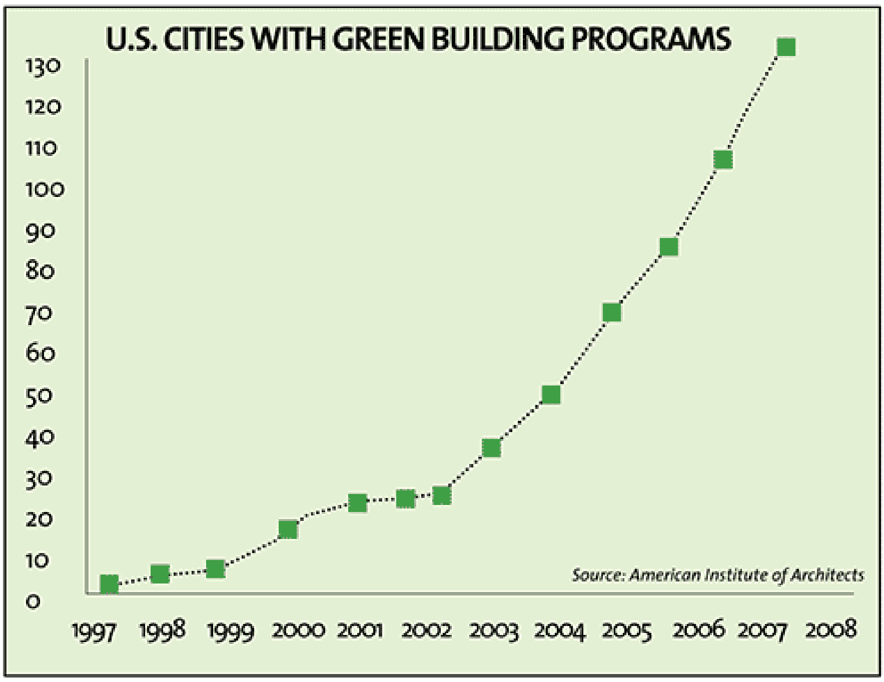

Figure 2 Green building programs in the U.S. [Hill 2008]

There are several positive sides in wood: wood is light in relation to its strength properties. Energy consumption is much lower when building with wood, compared with concrete and steel. Building with wooden prefabricated elements the time can be reduced to one third of the time to build with traditional materials. In addition, wood is a beautiful and calming material. [Laukkanen 2013]

Recently, wood has turned out to have positive effects on the health as well. For instance in Australia a study showed that in a wooden classroom, pupils' heartbeats were approximately 6 beats less in a minute than in the conventional classroom.

According to this Norwegian research, wood effects positively to the psychology of a human being. [Kairi et al. 2013]

Wood is an environmental friendly, renewable material that binds carbon dioxide. It is, however, also sensitive to the surrounding conditions. It absorbs moisture, which leads to dimensional changes. In the long run, the dimensional changes are not the only challenge of using the material. After a while in a moist condition, wood starts to mould, decay and attract other microbes deteriorating the material. Therefore there is a clear desire to hinder the moisture uptake; the research is running at full speed. New coatings, treatments and products are being developed.

2.2 Structure of wood

Trees consists of four main parts: root, trunk, branches and bark. These parts have different functions on the tree. In this study the focus is naturally on the trunk. The trunk is supporting the wood to stand still and bearing the load of branches, which can be substantially heavier during the wintertime due to the snow. The trunk protects the wood from outside stresses (e.g. wind). The trunk also conducts the moisture up to the leaves; the distance can be even 100m in large trees. [Jalava 1952] The trunk can be divided into two different parts: sapwood and heartwood. In sapwood, the cells store and conduct the needed carbohydrates. Inside sapwood is the heartwood, normally 20-50% of the trunk's diameter. The sap-/heartwood ratio depends among others on the age and species of the tree. The heartwood is literally the heart of wood, which is protected by the surrounding sapwood. In the heartwood, there are extractives that keep the fungal and insects away. The heartwood is often drier than the sapwood. [Dinwoodie 2000] Besides the sap- and heartwood, also the annual ring can most often be recognised, depending on the species though. As the weather changes, so does the growing. During the springtime the growing is fast and the material developed is more fragile. Among the non-coniferous trees the earlywood consists of more and larger vessels compared to the latewood. Larger vessels enable the accelerated movement of the liquids and nutrition, hence the formation of the wood material. When the high paced growing season is ended, wood needs to strengthen the material, with more robust cell tissue. Early- and latewood forms an annual ring, which can often be distinguished by eye. [Jalava 1952] In non-coniferous trees, the interface of early- and latewood is sometimes hard to detect, thus they are studied as one entity. [Kärkkäinen 2003] As a term, the annual ring is somewhat misleading, since in some latitudes there might occur fewer or superior rings due to different periods of growth. [Eshete, Ståhl 1999]

The above-mentioned vessels are one of the four main cells in wood, or more precisely in hardwood. They are short but wide: 0.2-1.2mm x maximum 0.5mm. Also fibres are present solely in hardwood, where their task is to support the tissue, their length is about 1-2mm. The two other cells, parenchyma and tracheid, are present in both, hardwoods and softwoods. Parenchymas are small, 200x30 µm, formed as a block to storage the food. Tracheids are larger, 2-4mm, not widely spread in hardwood though;

they conduct the food further and act as a support. The proportion of these four cells varies according to the species generating different properties to the wood material. The direction of the cells varies according to the wood species. Within softwoods approximately 90% of the cells are in the vertical direction, including all species. Among hardwoods there is more variance: 80-95% is in the vertical direction, depending on the wood species. [Dinwoodie 2000]

The cell walls consist of primary walls and secondary walls. The latter can be divided into three different layers: outer (S1), middle (S2) and inner (S3) layers shown in Figure 3. Figure 3 shows also the orientation of the microfibrils. The S2 is the main part of the cell wall, consisting of 30-150 lamellas. It is also the main factor for the properties of wood material. The angle of the microfibrils in the S2 wall is from 10 to 30°. The orientation of the microfibrils has an important influence on the strength properties, but also the swelling and shrinking properties of wood. The angle is smaller in latewood, thus it shrinks less in accordance to the wall thickness in both radial and tangential directions. [Dinwoodie 2000, Kärkkäinen 2003]

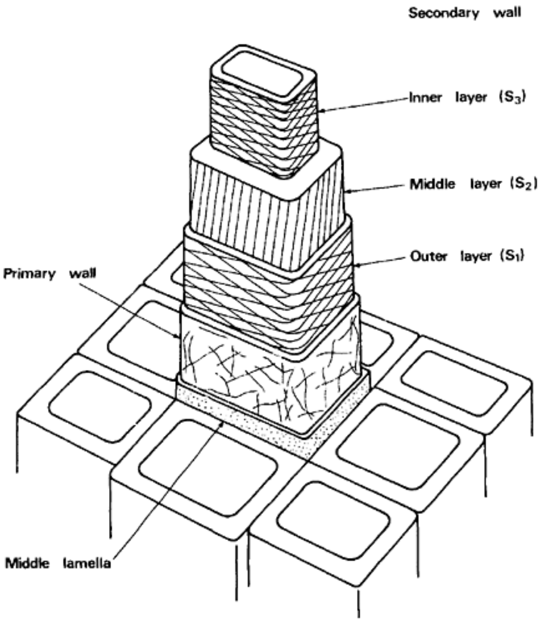

Figure 3 Structure of the cell wall [Dinwoodie 2000]

When studying wood material more closely, in a molecular scale, it can be seen that the material consists of four different components: cellulose, hemicellulose, lignin and extractives. Cellulose is the main component in wood material (40-44% of the dry weight of wood), acting as a frame of the cell wall. Lignin makes the cell walls rigid. 18-25% of hardwoods’ dry weight is lignin; in softwoods, the proportion is clearly higher: 25-35%. The hemicellulose bonds cellulose with the lignin. The amount of hemicellulose in softwoods is 20-32% and in hardwoods 15-25%. These three components behave differently in relation to the moisture. This will be discussed more closely in the following section. [USDA 2010].

2.2.1 Moisture

Wood is a hygroscopic material. It absorbs water (in different forms) from the surrounding space. The moisture absorption is the strongest in the longitudinal direction. There are two types of moisture in wood: free and bound water. In the cell cavities, there is the free water, the term “free” since it is not chemically bonded to the wood material and can be either in liquid or vapour form. The bound water, situated in the cell walls, is chemically and physically bounded to the hydroxyl groups of cellulose. As the nomenclature describes, the free water is easier to remove.

When the cell walls are filled, wood attains its fibre saturation point (FSP). Beyond the FSP, wood absorbs only free water to the cavities, which does not change the dimensions of the wood piece. The FSP is a somewhat radical point when it comes to the properties of the material: they change dramatically. Foremost, above the FSP the changes in MC do not effect essentially on the mechanical nor physical properties of the wood material. Below it, the strength properties among others start to improve. [Dinwoodie 2000, Jalava 1952] When the bound water is removed, the microfibrils come closer, which reduces the volume and in the meantime enhances the bonding between the fibres and therefore the strength properties of the material as can be seen from the Figure 4. [Dinwoodie 2000] Due to this phenomenon, the MC of the test specimens has to be taken into account when evaluating the strength properties of the sample.

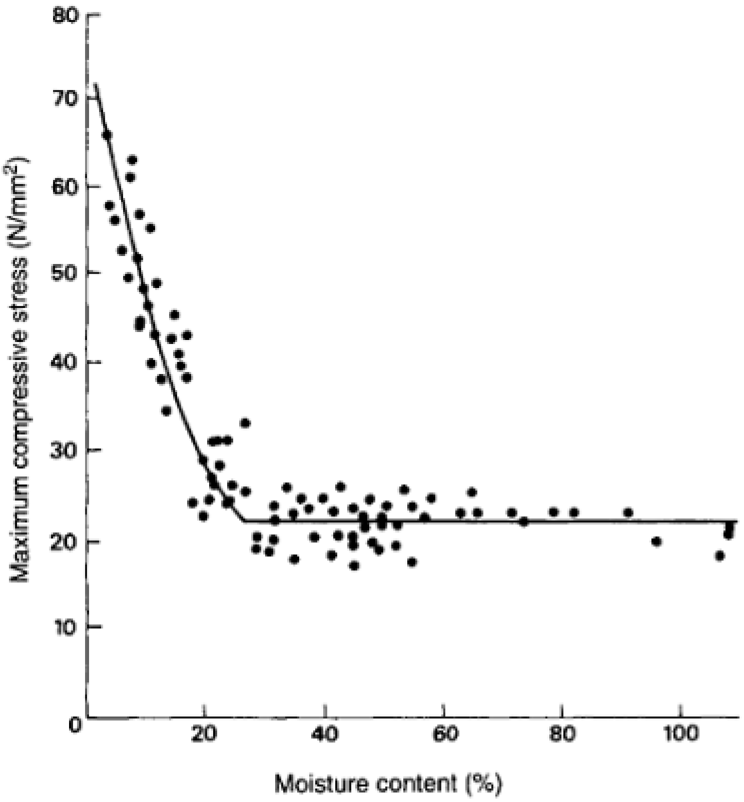

Figure 4 Maximum compressive stress in relation to the moisture content [Dinwoodie 2000]

The moisture content of wood can be measured through several different tests, but the main common one is the oven-dry-method, in which the mass of the specimen is measured before and after drying it at 103°C. The moisture is calculated by using the following function:

$$mc = 100(m_g - m_0)/m_0 \qquad (1)$$

, where mc is the moisture content in %,
m_g is the mass of the moist wood and
m_0 is the oven-dry mass [USDA 2010]

The FSP of birch and beech are close to each other, around MC 32-35%. When compared with the other species it is high; only some pines might be above it (25-49%). Oak and ash are at the other end; their MC at the FSP is 23-25% [Jalava 1952]. Nevertheless, through the contribution of temperature changes and certain chemicals the FSP can be modified.

The main factors affecting the MC of wood material are naturally its compounds, cellulose, hemicellulose and lignin, and their proportions. As told above, these three components behave differently in relation to moisture. Lignin is the most hydrophobic.

Cellulose and hemicellulose on the contrary are hygroscopic, thus they are mainly responsible for the moisture uptake. [USDA 2010] The differences in the behaviour with the moisture are due to the presence of OH groups, which have an important effect on the wood properties. Due to the branched structure of hemicellulose, it contains most of accessible OH-groups compared to the cellulose and lignin. It also appears to be the coupling agent between the microfibrils and lignin. There are also inaccessible OH groups, for example in the crystalline core of the microfibrils. These inaccessible hydroxyl groups cannot react with water [Hill C. 2006]

There are different types of flows in wood. Dinwoodie [2000] distinguishes these three according to the type of moisture: above the fibre saturation point there is the liquid free water that flows in the cell cavities. Second type is the water vapour diffusing in the lumens, this occurs in both stages, above and below the fibre saturation point. The third one is the bound water diffusing from the cell walls below the FSP [Dinwoodie 2000]. Siau [1984] continues the distinction of the flow further, according to needed kinetic energies to transfer the fluid: laminar/viscous, turbulent, nonlinear and molecular slip flow, i.e. Knuudsen diffusion. Viscous is an even flow, based on the internal fluid friction. In turbulent flow, the required energy is increased since the fluid is in turbulence. This occurs in earlywood vessels. The nonlinear flow is present when the fluid is moving to narrower capillary. [Siau 1984]

The equilibrium moisture content, EMC, of wood is the stage at which it does not gain nor loose moisture, i.e. it absorbs the same amount of water molecules as it desorbs. EMC varies slightly between different wood species: the more there is hydrophobic lignin the lower is the EMC. Other factors affecting the EMC are the temperature and relative humidity (see Figure 5). As the temperature rises, EMC decreases if the relative humidity is constant.

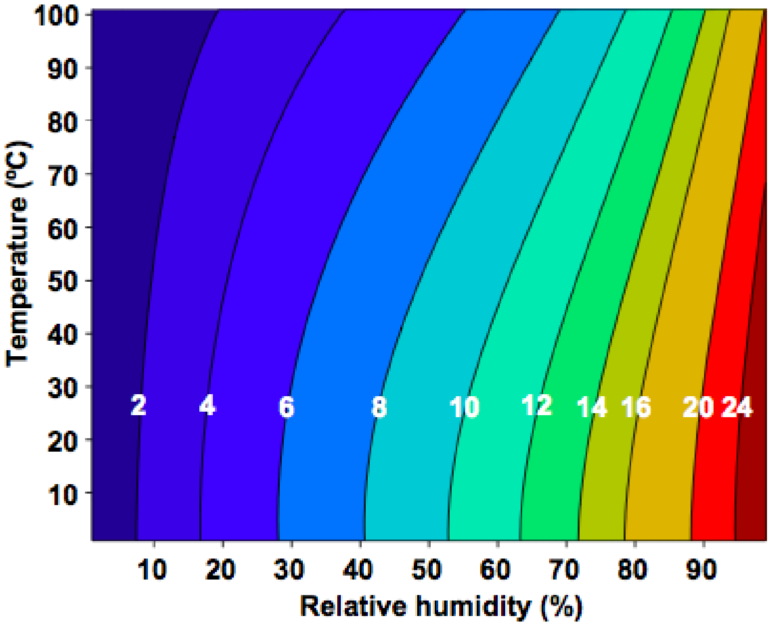

Figure 5 EMC of wood, according to RH and temperature. [USDA 2010]

The equilibrium moisture content of wood also depends on the stage the wood is in, whether it is absorbing or desorbing moisture. In absorbing stage the equilibrium moisture content in specific temperature and relative humidity, is lower as it is in desorption stage, as can be observed from the Figure 6. [Dinwoodie 2000, Kärkkäinen 2003]

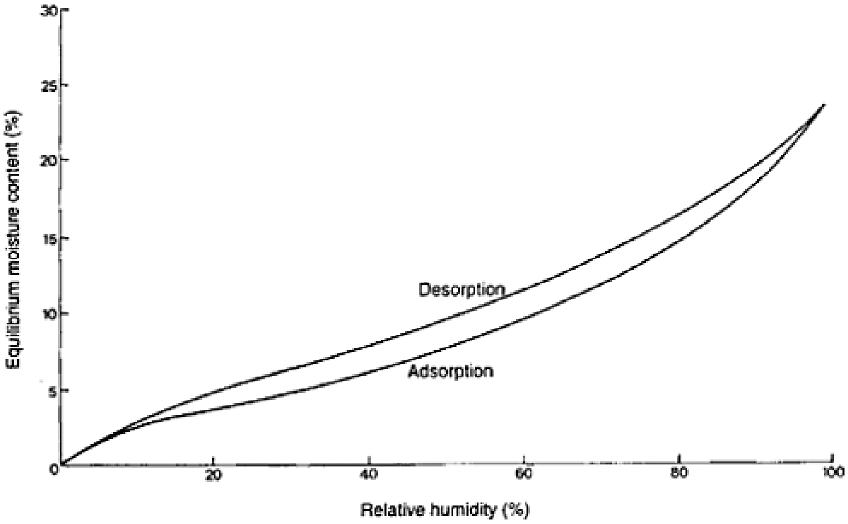

Figure 6 Equilibrium moisture content of wood according to the relative humidity (isothermic) [Dinwoodie 2000]

In addition to the temperature and RH, there are also other ways to modify the EMC. For instance: the use of low alkaline adhesives decreases the EMC. However, the easiest and simplest way to decrease the EMC is the manufacturing conditions, i.e. high temperatures in drying and pressing. However, the high temperatures may reduce the wood quality and evoke further cracks, which increase the diffusion rate. Also the stress can decrease the EMC if the swelling of the material is restrained. On the contrary, if the material is under tension, it tends to have higher EMC. [Absetz 1999]

2.2.2 Stability

Wood swells and shrinks according to its moisture content. When wood swells, great powers are involved. Some studies show that the force would be 1,630 atm. [Rowell et al. 1985] In ancient Egypt people took advantage of it – they used the power of the swelling to break off rock [Jalava 1952]. Most often the changes have negative effects though, especially if the end-use conditions are not constant: e.g. window frames and doors designed to certain dimensions become either too small or too large due to changing weather conditions, especially in northern countries.

The higher the density of wood, the more it swells when it becomes moist. The swelling and shrinking vary according to the species. Birch shrinks slightly more than beech, even though their densities are close to each other. [Jalava 1952] According Fagerstedt et al. [2005] the density of birch is 480kg/m^3, and beech’s 600kg/m^3, which would indicate that the latter would have clearer dimensional changes.

The swelling and shrinking of wood is anisotropic, i.e. it swells and shrinks differently in different directions. There are three main directions: in the tangential direction the swelling is the strongest, 8-12%, radially it is approximately a half, 4-6%, in the longitudinal direction it is only 1%. [Zhang et al. 2006]

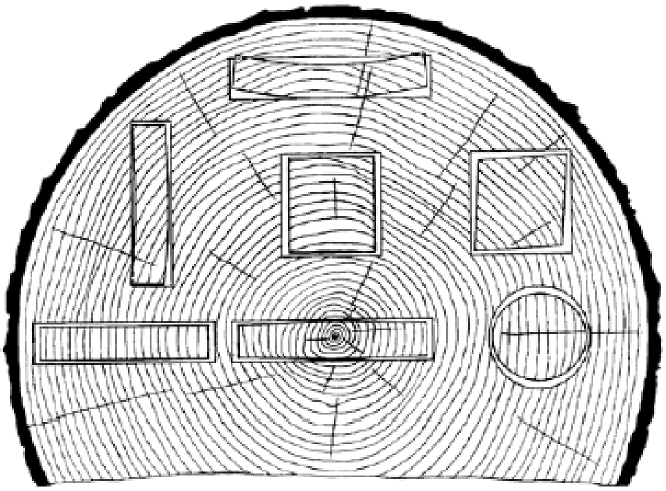

Figure 7 The shrinking of pieces sawn from different parts of the log. [USDA 2010]

From Figure 7 above, a careful observation can be made about the stability of the inner part, heartwood. Among species in which the boundary between sap- and heartwood is visible, the density in the heartwood is said to be somewhat higher than in the sapwood. Regardless the higher density, the shrinking is slightly lower in heartwood. This results from the greater amount of extractives in the fibres. [Jalava 1952]

Naturally, if the dimensional changes in a material vary in different directions, cracking and warping of the material among others are evoked. This is peculiar to wood material. Since decades, new and more efficient ways have been studied to hinder the moisture penetration. Paint and varnishes were one of the most common ways to retard the sorption. [Jalava1952] Already in the 1980's studies had shown that hydroxyl groups are responsible for the moisture uptake. [Rowell et al. 1985]

One of the reasons to develop plywood was to hinder the dimensional changes. The plies bonded perpendicularly to each other mechanically oppose the swelling and shrinking.

2.2.3 Strength properties

The strength properties of wood material are a complex system since the material is more like a construction and not a substance. [Kärkkäinen 2003] At a larger scale, the main factor effecting the strength properties is the density of the wood material. If the density is known, an estimation of the strength properties can be done. The density, as well the content of extractives and other properties, changes according to the wood species. When studying the strength properties on a microstructural scale, it can be seen that it is the cellular structure of the material that has an important influence on the behaviour. The bonding is different along and between the microfibrils. The covalent bond, which is the strongest chemical bond [Oksman Niska et al. 2008] is along the microfibrils. The hydrogen bonds between the microfibrils are only a fraction of the covalent bond. Further, the angle of most of the microfibrils is small in relation to the longitudinal axis and therefore it is more difficult to break the cell wall when the load is applied along the axis. [Dinwoodie 2000] In the longitudinal direction wood can have even 20 times better strength properties compared with the other two directions, radial and tangential [Freas 1956].

Moisture is also an important factor, as described in the previous subsection (2.2.1). Therefore the strength test results have to be defined at a certain moisture content to ensure the results are comparable with other studies. If the target MC is not reached, can the corresponding strength values be achieved through calculation [Skaar 1988, Dinwoodie 2000]. Below MC 5-6% there are indications that the strength properties might decrease. [Skaar 1988] Dinwoodie states that the decrease occurs only below a MC of 2% [Dinwoodie 2000]. This could be derived from stress concentrations. [Skaar C. 1988] The effect of the increase in moisture content also depends on the type of the strength measured. The tensile strength does not decrease as much as the bending and compressions strengths do. [Kärkkäinen 2003]

Other factors amongst others are the temperature of the specimen; in colder temperature the strength values are superior, however the difference is not as remarkable in dry wood. The irregularities of wood also effect on the strength properties, as an example the knots reduce the elasticity. [Kärkkäinen 2003]

When bending a wood specimen, there are two different types of forces that evoke: compression and tensile strength. Compression is developed on the concave side and tension to the convex side. The neutral spot at the beginning of the bending is in the middle of these two sides, but it moves towards the tensioned side when the bending is proceeding, until the specimen yields. Both tensile and compression strengths are superior in the grain direction, compression strength being approximately half of the tensile strength. When manufacturing plywood for load bearing structures (e.g. walls and floors), the plies with the best strength properties are placed on the outer layers of the board, because of the tension and compression concentration on the surfaces. [Kärkkäinen 2003] Birch plywood and its properties, including the strength properties are described more closely in the following section.

In the wood product industry the strength properties of the materials are mainly defined through statistic tests, e.g. three- and four-point bending tests. Impact test are less common in wood product industry. Few resources were found though. Some repositories indicate that the dynamic strength would show even more than 20% higher values than the static tests. On the modulus of elasticity, the effect of the impact is slender, values being similar as in static tests. According to Kärkkäinen [2003], there is one interesting difference between the static and impact strengths: the influence of the moisture content, which does not seem to effect on the energy that the specimen absorbs.

The grain direction affects the results tremendously and therefore greater variance is expected. Furthermore, all the defects (e.g. weathering and decay) have a stronger influence on the impact properties. [Kärkkäinen 2003]

Caufield [2010] tested Izod impact resistance by using aspen fibre-polypropylene composite. The increase of MAPP (maleic polypropylene) showed an improvement in all the strength properties (flexural and tensile strength), including Izod toughness. When decreasing the portion of the aspen fibres, only Izod toughness decreased. [Caufield et al. 2010]

In the research of F.Y.C. Boey [1985], he investigated the relationship between polymer loading and strength properties. This relationship was found to be linear regarding compressive and bending strengths. However, the impact energy did not show any visible difference according to the amount of polymers. The reason behind the first mentioned ameliorations might due to the strong interface. [Boey 1985] Through polymers and other additives, wood material can be modified to better respond to the requirements in the end use.

2.3 Plywood

2.3.1 Manufacturing process

The plywood manufacturing process consists of several stages and the temperature increases severely in some stages. In every phase the material has to be treated adequately to achieve plywood of good quality at the end of the process. There are slight variations in the process depending on the wood specie and the end use of the plywood [Koponen 2002]. In this thesis the main focus is on birch plywood.

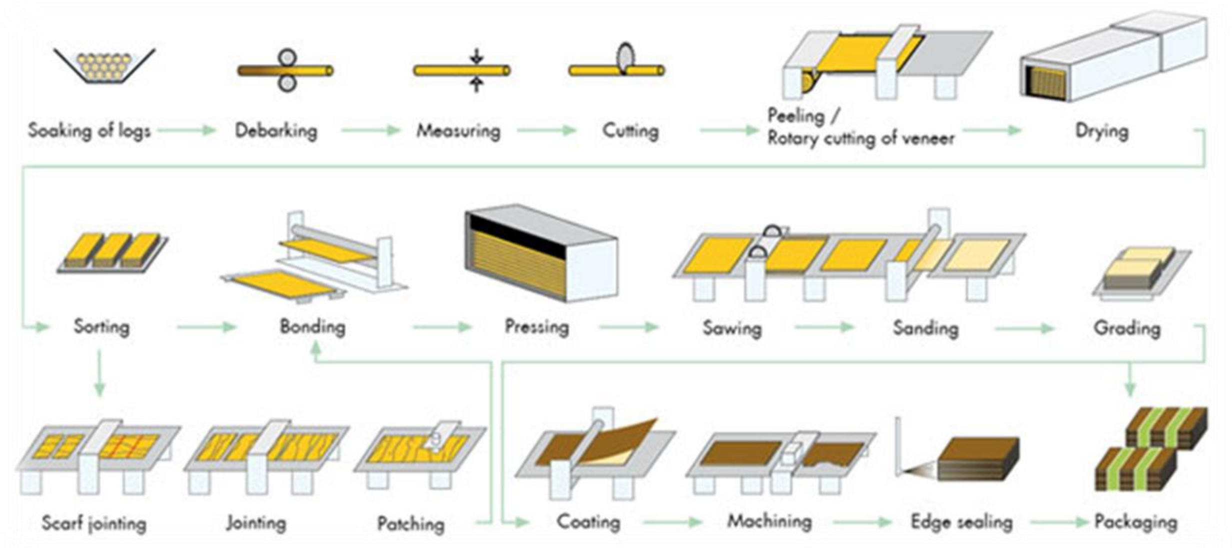

Figure 8 Plywood manufacturing process [UPM Webpage]

The manufacturing process begins with soaking the logs in warm water to soften the wood material and make it more elastic. Soaking eases the debarking of the log, but first of all it enhances the quality of the veneers. The target moisture content of the log is at least 30%. The temperature of the soaking tank is determined according to the wood species; it varies from 40 to 70°C. If the temperature is too high or low, it may affect the colour of the log and therefore the final plywood quality. Rohumaa et al. [2007] found that logs soaked at 70°C had enhanced bonding compared to the ones that were soaked at 20°C. The energy used for soaking is approximately 15% of the total energy consumption in the manufacturing process. However in many cases the heat energy can be achieved from other processes (e.g. veneer drying), since the soaking temperature is lower. After soaking the logs are debarked and cut into right dimensions. In northern countries the low temperatures of winter time freezes the bark and therefore disables the debarking prior to the soaking. The length of the log determines the length of the veneer, i.e. the grain direction. The most common dimensions are 50” and 60”. This is normally the shorter edge of plywood. [Koponen 2002]

Then the logs are peeled. Peeling is often considered to be one the most important phases in plywood production, since it determines the veneer quality. The peeling is done along the annual ring. The actual lathe blade peels the log, but there is another blade as well, a counter blade or a pressure bar, which presses the peeled veneer. The counter blade and pressure bar ease the peeling and therefore improve the quality of the veneer, but if excess force is used, cracks in the veneer matt are evoked. Peeling parameters, i.e. speed, knife angle and thickness are constantly determined to attain an adequate gain and high quality veneer. The average yield of birch logs is 58%. The peeled veneers are sorted mainly according to its surface quality and smoothness. The transverse tensile strength is also an important factor, since the veneers should endure the entire process, from drying till the hot-press of the plywood. The detection of the veneer is demanding, since in green stage the flaws are more difficult to trace. They become more apparent after sanding the plywood. In an economic point of view, it is extremely expensive to detect the flaws at the end of the process. [Koponen 2002]

The veneer produced is dried. The drying is based on the hygroscopicity of wood material. When the temperature is raised, the moisture content decreases to achieve the equilibrium moisture content. The drying is divided into four different stages: first the temperature of the veneer is increased, but there is no actual drying yet. In the second stage the temperature of the veneer is augmented close to the boiling point of water and the drying is strong, till the fibre saturation point. After attaining the FSP the temperature of the veneer approaches the surrounding temperature, around 200°C. In the last phase, the temperature is decreased to enable the veneer handling. The bonding may also be inadequate if the temperature of the veneers has been too high at the beginning of the gluing process. Too high temperature of the veneers dries the adhesive, which leads to a too precipitated reaction of the glue. [Veistinen et al. 1999, Opetushallitus]

The overall shrinkage of the veneer (MC 5%) is 8% among birch veneers and 6% for the softwood veneers. [Koponen 2002, Juvonen et al. 1985]

If the veneer is too dry or moist, the adhesion will not be sufficient, and also the strength properties deteriorate. The veneers should be dried to a moisture content of approximately 2-6% depending on the wood species, thickness, adhesives and end-use conditions of the board. After drying, the veneers are sorted according to surface quality and moisture content. Generally ca. 63% are categorised as core veneers, 23% of BB/III quality. The better quality surface veneers (quality S/II) present normally only 2% of all the veneers. Sometimes the sorting is done according to the density, which defines more or less the strength properties of the ply, depending on the end-use. To attain better yield, some of the veneers are refined after drying. The flaws (e.g. holes, knots, bark and rotten) can be patched after removing them. The smaller pieces of veneers can be jointed together by composing from smaller veneer pieces. The quality of the refining is important, since the composed veneers should stand till the end the process. [Koponen 2002]

The gluing process is the most time consuming, but also the most important stage of the process along with the peeling. It defines the performance of the product. The assembly of plywood starts from mixing the glue (adhesives are discussed in subsection 2.3.3). The glue is normally applied on the veneers with a roller spreader, curtain coater or with a liquid extruder. The minimum temperature of the adhesive is 32°C, 38°C being the target. [Baldwin 1981] Naturally the temperature affects the viscosity of the glue, which in turn, affects the glue spreading. As the viscosity increases, so does the distribution, i.e. there is more glue per square meter. Too high viscosity may lead into an uneven spreading of the adhesive, which reduces the quality of the product. On the contrary, if the viscosity of the adhesive is too high, it risks penetrating too deeply into the veneer, which leads to a poor adhesion between the veneers.

The maximum open time (i.e. the time from spreading the glue till it is exposed to pressure in the pre-press) for the glue is 30 minutes, after which it starts hardening. After the spreading, the plies are stacked. First the stack is pre-pressed cold, under pressure for 5-10min. The pre-press initiates the curing of the adhesive and equalises the moisture content between the veneers. It also enables the insertion of the panels to the hot-press. The fourth important function of the pre-press is the enabling of the storage of the panels for up to 12 hours, which facilitates the production planning. [Koponen 2002, Juvonen et al. 1985]

In the hot-press the temperature, pressure and exposed time are precisely defined according to the thickness and nature of the plywood. [Koponen 2002, Juvonen et al. 1985] The temperature depends on the adhesive: for phenol formaldehyde the temperature is 125-130°C whereas for UF it is slightly lower: 110-125°C. Also the pressing time is somewhat higher for the PF-bonded plywood. The temperature is transferred into the board and pressure is increased, which leads to decreased viscosity of the adhesive. The adhesive is then able to penetrate into the veneers. This starts the condensation reactions of the adhesive leading to an increase and cure of the adhesive. [Koponen 2002] Too moist veneers risk of causing blowouts after the hot-press, which risk rupturing the adhesion. Therefore the pressure is almost entirely released at the end of the hot-pressing, to ease the controlled vapour evaporation, hence prevent the breakage of the board.

After hot-pressing the panels are cut into desired dimensions, sanded on both sides and finally graded according to the surfaces. After the grading, the panels are sent either to packaging or upgrading, the latter varies from coating and filming the plywood to scarf jointing. The finished panels are then packed and sent to the customer. [Koponen 2002]

During the plywood manufacturing process, there are several stages in which the residuals of the raw material are salvaged to either exploit on the site, or sell further, including pulp and energy industries.

2.3.2 Properties of a birch plywood

2.3.2.1 *Mechanical properties*

Orienting the plies affects not only the stability of the plywood, but also the strength properties, which are attained in both directions due to the cross laminating. Apart from a few exceptions, in plywood there is always an uneven amount of plies, thus the face veneers are in parallel direction. This naturally affects the strength values: when the bending direction is parallel to the face grain, the values attained are somewhat higher, depending on the plywood thickness. In compression and tension tests the distinction is less obvious. At the plywood mill the main purpose for conducting bending tests is to ensure proper bonding between the plies.

According to the Handbook of Finnish plywood the bending strength of 15mm thick birch plywood (with 11 plies) is 41.3N/mm^2 parallel and 33.8N/mm^2 perpendicular to the face grain. Modulus of elasticity (MOE) in bending is 10 316N/mm^2 and 7184N/mm^2. These values are attained at MC 15%. The tensile strength is close to bending strength values: for 12mm thick flat plywood the tensile strength is 40N/mm^2 and 35N/mm^2 in the two directions. Compression strength is a third lower at 27.7N/mm^2 and 24.3N/mm^2. [Veistinen et al. 1999]

Perhaps the most common tests used in plywood industry are the bending test: three- and four-point bending test (see Figure 9). The tests are not the same and some sources claim that the three-point bending test underestimates the MOE-values by 19% when compared with the values attained in four-point bending. [Brancheriau et al. 2002] Some resources claim that the four-point bending test gives more reliable results [Teknologiateollisuuden 10-vuotissäätiö 2009].

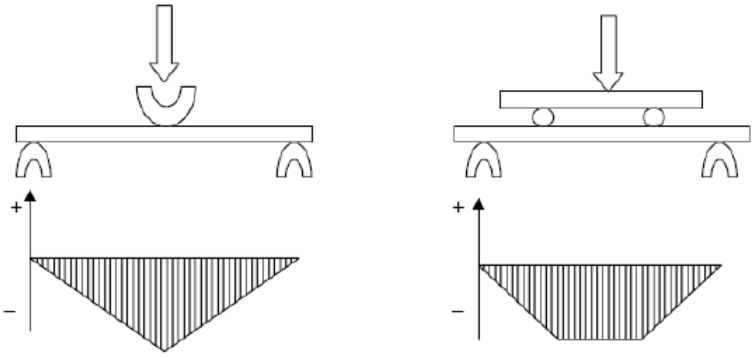

Figure 9 Loading in three- and four-point bending tests [Teknologiateollisuuden 10-vuotissäätiö 2009]

In four-point bending test the specimen is larger, thus the probability that there are more defects in the heterogeneous specimen is also higher. One factor affecting the strength properties of wood material is the discontinuity spots. [Kärkkäinen 2003]

2.3.2.2 Moisture transport

The main raw material of plywood is wood, thus the moisture behaviour of plywood resembles that of solid wood. However, the adhesive and high processing conditions (up to 220°C) differentiate them from each other. The behaviour of plywood can be expected to resemble the behaviour of wood until the first glue-line.

Due to the nature of wood material and the way of fabricating plywood (from the rotary cut veneers), the diffusion is the strongest through the edges, $4.35*10^{-10}$ m^2/s. Through uncoated faces, the rate is $0.9*10^{-10}$ m^2/s [Veistinen et al., 1999]. Absetz states [1999] that the difference is even clearer: $1.1*10^{-9}$ m^2/s vs. $7.0*10^{-9}$ m^2/s. The rotary peeling cracks on the veneer increase the diffusivity of the plywood. The occurrence of the cracks depends on several factors, i.e. the species, density, veneer thickness, surface quality, etc.). According Absetz [1999], for a plywood, on which there is one crack of 0,1mm every 1,5mm, the diffusion coefficient is $12.2*10^{-11}$ m^2/s, which is almost double compared to a plywood without cracks, $6,6*10^{-11}$ m^2/s.

The high temperatures during the manufacturing change slightly the behaviour of wood material, as well as the proportion of adhesive; if the ratio of veneer and adhesive decreases below 0.3, the diffusion rate rises exponentially. [Absetz 1999]

As for solid wood, the moisture absorption has an effect on the stability of plywood as well. Normal birch plywood swells length and width wise 0.017% per 1% change in MC between MC 7 and 18%. Thickness swelling is clearly more: 0.41% per 1% change in MC between 7 and 27%. The flatness of normal plywood is the best at MC 9-11%. When plywood is exposed to dimensional changes also a deterioration of the strength properties is likely to occur as a result of weakened bonding between the adhesive and wood material. [Veistinen et al. 1999]

If the manufacturing conditions cannot be modified, can the cell cavities be occluded, by sealing the edges with paint. The edge sealing hinders the diffusion rate. Even though the paint sealing reduces the diffusion, it is not strong enough to be used in the exterior or other demanding uses. [Veistinen et al., 1999] A simple and reasonably priced way to hinder dimensional changes in plywood is coating it. The water absorption rate of the conventional, uncoated birch plywood is $1940g/m^2/24h$. If it is coated with a phenolic film of $120g/m^2$ the absorption diminishes down to $36g/m^2/24h$, which is less than 2% of the uncoated one. If the coating were $170g/m^2$, the absorption rate would be $26g/m^2/24h$. There are also other coating possibilities. Järvelä et al. [1999] studied a thermoplastic coating on plywood. The study showed that the addition of maleated polypropylene wax enhanced the adhesion between wood and the polypropylene. [Järvelä 1999] Thermoplastic is an interesting element in WPCs and it will be covered in Section 2.4.

2.3.3 Adhesives

There are different kinds of adhesives used in the plywood industry. Some of them are delivered to the mill in a liquid form and others in solid phase. Normally the adhesives are not ready-made in the gluing factory to enable longer lifetime for the adhesive and therefore better adjustment to the production capacity of the moment. [Juvonen et al. 1985] The delivered resins are stored at the mill at 12-18°C. When they are taken into production, the needed hardeners, diluting agents, additional water and fillers are mixed with the resin. [Koponen 2002]

The adhesives can be divided into two different categories: the physically bonding adhesives (e.g. starch and polyvinyl acetate) and the chemically bonding adhesives. In the plywood industry the adhesives used are mainly of the latter type. The mechanical adhesion is said to be only 10% of the total adhesion. There are three main adhesives: phenol and urea formaldehydes and polyurethane. [Koponen 1989]

Formaldehyde appears as a gas in room temperature. It has a pungent, irritating odour and it is easily soluble to the water. The formaldehyde-water solution is called formalin. Formaldehyde is classified as II class toxic and III class flammable material.

Urea is colourless and strongly water-soluble as well. It is manufactured from carbon dioxide and ammonia. It is not toxic, thus causes no health damage. Urea bonds to formaldehyde through amino bonds. The advantages of urea-formaldehyde adhesives are their low cost, fast curing and colourless glue-line (see Figure 10 below), however it does not resist moisture and therefore it is used solely in indoor applications (dry and moist conditions) [Finnish Forest Industries Federation 2007]. Due to the presence of formaldehyde it is classified hazardous. [Koponen 1989] Due to the poor resistance to moisture, small quantities of melamine are added to the adhesive to enhance the performance of the glue-line against moisture [Dunky 1998]. Mansouri [2006] studied the effect of polymeric isocyanate on the properties of UF-bonded beech plywood. He found out that when adding 10-15% of pMDI to the UF adhesive, the plywood became more resistance to moisture: when normal UF bonded plywood yielded after 11 minutes, the pMDI treated plywood withstood 19 and 27 minutes (UF/pMDI 90/10 and 85/15). [Mansouri 2006].

Obersriebnig et al. [2013] states that if the bonding between UF adhesive and wood is strong, i.e. the UF adhesive has penetrated in to the cell cavities, a higher proportion of wood failure occurs while load is applied to the specimen.

Melamine resin is similar to the urea resin. It is colourless and based on ammonia. The main difference compared to the urea resin is the resistance to moisture. Melamine resin can be used in moist conditions. Another distinction is the curing: melamine can be cured above 130°C without hardeners. However, due to the clearly higher price of melamine, it is rarer in plywood production. [Koponen 1989]

Phenol is a brown coloured compound (see Figure 10 below) fabricated mainly from isopropylbenzene. It has a poor water-solubility in cold temperature, thus the temperature has to be increased to above 40°C to enable dissolution. As with formaldehyde, phenol is also classified as II class toxic. However, due to the manufacturing process of the adhesive, there is only a minor amount of free phenol and formaldehyde. The advantage of phenol is its moisture resistance, however the price is clearly higher compared to urea. Phenol is used not only in plywood adhesives, but also in coatings. [Koponen 1989]

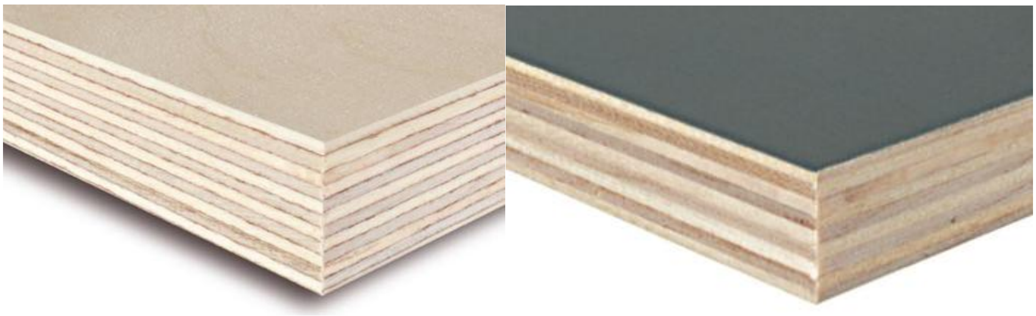

Figure 10 The difference outlook of phenolic and urea formaldehyde adhesives. UPM PF-glued birch plywood on the left and UF-glued plywood at the right [UPM Homepage]

Besides these above-mentioned adhesives, there are several other adhesive, but they are not in common use, for instance polyurethane adhesives. They are used mainly to bond coatings on the plywood surface. Due to its high price, it is more uncommon. The average curing time for PU-adhesive is 2-3 hours at 100°C.

Plywood manufacturing conditions vary tremendously, especially in Nordic countries and other regions having four seasons. Thus the benefit of the adhesives fabricated at the place is that they might be more adaptive to the seasonal changes, as e.g. the proportion of water can easily be adjusted.

Wood is a heterogeneous material, thus its properties have to be taken into account while designing the adhesive and how it is used in the process. There are a few important properties of wood that has to be taken into account while designing the gluing process. These are porosity, since the adhesive penetrates more easily on a porous material. The porosity can be derived from the density. The density as well the porosity varies also between the early- and latewood, thus the adsorption of the adhesives changes dramatically on materials having strong differences along the annual rings. The adhesion capacity also changes between the heart- and sapwoods. The heartwood cells are already filled, thus their ability to absorb adhesive is diminished. As can be deduced from the above mentioned, different faults, e.g. knots and reaction wood cause divergence on the adhesion. Other, more overall factors are the chemical composition of the wood and how it is handled before the gluing process. [Koponen 1989, Rohumaa et al. 2007]

2.4 Wood bonding with thermoplastics

Wood plastic composites have been developed since decades, but only during the last decade have real commercialized products become widespread. Due to the higher prices and inferior availability of natural durable species, wood plastic composites and plastic lumber are replacing the costly materials, e.g. in deck and home building. Treated lumber market share on deck surfaces is 40%, WPCs' 28% and natural durable species only 13%. [Indroneil et al. 2009]

Wood plastic composites are also used in automotive industry, door and window frames, furniture and construction. [Grubbstrom 2009] The spread depends on the continent: in Europe the wood-thermoplastic composites are mostly used in automotive industry, whereas in North America the leader is construction industry. The continent also affects the main raw material: in Europe composites are manufactured most of all from natural fibres, when in North America, the main material is wood. In Asia, it is a duly rice hull and bamboo. If composite is fabricated from fibres, its properties can be assumed to be superior. However, it requires more effort to extract the fibres at the first stage.

The wood-thermoplastics can be divided into two categories depending on the proportion of the thermoplastic content: high or low content. The first one is predominant in the markets. In this category, the thermoplastic is continuous and the wood content less than 60% by weight. The function of wood is to reinforce the thermoplastic matrix. These reinforced composites have several superior properties than unfilled materials: they not only make the composite stiffer and enhance its strength properties; they also improve its thermal stability. Wood however induces some challenges in the process: excess moisture has to be avoided and the temperature has to remain below 200°C throughout the entire process to avoid degradation of wood. The composite of the second category contains less than 30% of the thermoplastic by weight, thus the thermoplastic acts further as a binder, as in plywood as example. [USDA 2010]

2.4.1 Adhesion in thermoplastics

Thermoplastic polymer is a material, which softens while heated and cures when cooled. The entire process is reversible and can be done several times. E.g. polyethylene is a thermoplastic. The opposite of the thermoplastic is thermosetting polymer. After having cured, the thermoset polymer stays in its final stage, due to the crosslinking between the polymer chains. As from the nomenclature can be deducted, this is an irreversible process. Phenol-formaldehyde is a thermosetting polymer. [Oksman Niska et al. 2008]

There are many different thermoplastics, as there are coupling agents [Lu et al 2005; Oksman Niska et al. 2008]. In this section the focus is only on few of them to understand their utilisation and characteristics.

As stated in the subsection 2.2, wood consists of hemicellulose, cellulose and lignin. According to Follrich et al. [2006] the strong hydrophilic characteristic in wood is caused by the numerous hydroxyl-groups in the main components. Thermoplastic polymers are often hydrophobic, which leads to severe problems in the adhesion causing poor mechanical properties. Therefore it is vital to improve the adhesion, which can be done by using coupling agents as an example. [Kazayawoko et al. 1999, Klason et al. 1984]

2.4.2 Coupling agents

The use of coupling agents is based on a treatment of surfaces to promote the adhesion between a hydrophilic wood and a hydrophobic thermoplastic polymer [Lu et al 2000; Oksman Niska et al. 2008]. The promotion occurs when the coupling agents bonds the wood fibre to the thermoplastic polymer. Promotion means that after adding a coupling agent, the molecules of wood and thermoplastic polymer are able to form a covalent bond, a polymer chain entanglement or a strong secondary interaction, or a combination of these. [Raj et al. 1988]

From the Figure 11 below can be seen that without maleation polyolefin (MAPE) it is impossible to form a strong chemical bond to a cellulose molecule. In the polyolefin all the chemical bonds are saturated and therefore not likely to react with any other substance, unless external promotion is applied. In the maleated version there are double bond between the carbon and oxygen. These bonds are aiming for a simpler form of bond and therefore react easily with hydroxyl-group in cellulose molecule.

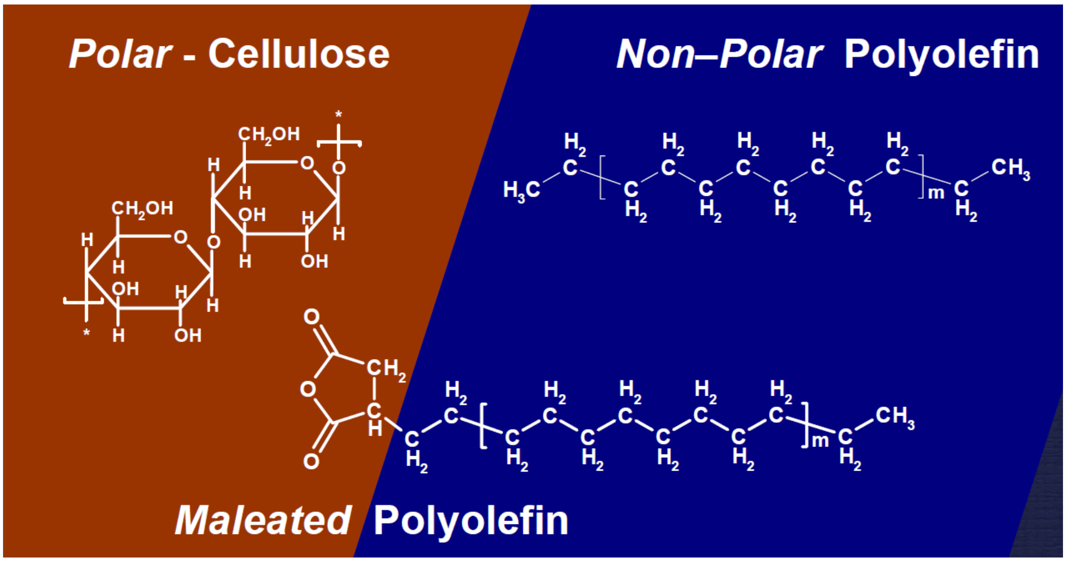

Figure 11 Demonstration of the use of coupling agent to enhance the adhesion [Keener 2003].

The interface and the mechanical properties of a composite are affected through the coupling agent type, function groups, molecular weight, concentration, and chain structure. The best results are achieved with high molecular weight, moderate acid number, and low concentration level. [DeVallance 2007]

John Z. Lu et al. [2005a] investigated wood-polymer composites with seven different coupling agents. Overall MAPE improved the interfacial adhesion more than oxidized polyethylene and pure polyethylene. MAPEs also improved the crosslinking structure at the interface, which increased the stiffness of the composite. The stiffness increased brittleness though. Within the research, the interfacial bonding strength increased by 140% on maximum and by 29% on flexural modulus compared with the unmodified samples. Among seven different coupling agents 226D (see the specifications below) attained the best results. In 226D, the molecular weight was 67600g/mol, molecular number 21700, backbone structure LLDPE, acid number 4.7mg KOH/g and MC of the thermo-mechanical pulp fibre was 2-3%. For the 226D treated composites, both storage modulus (E') and loss modulus (E') increased as the concentration of coupling agents increased. [Lu 2005a]

According to Zhang et al. [2006], a wood-polymer composite, where the wood had been impregnated with MMA (methyl methacrylate), had the lowest moisture absorption rate. As the HEMA (hydroxyethylene methacrylate) impregnated composite had the highest rate. [Zhang et al. 2006]

The study of Ruijuns [2010] showed that the coupling agents decreased the amount of voids leading to better adhesion. Through the enhanced adhesion, a better resistance to shocks and tension was achieved. Due to improved adhesion there were fewer voids and the penetration routes were blocked. The hydrophobic polymers on the surface also eliminated the OH-groups. These improvements led to a decreased absorption and desorption rate. [Ruijuns 2010] The positive effects of the coupling agents could be destroyed though by increasing their amount too much. [Järvelä 1999, Ruijuns 2010]

2.4.3 Adhesion mechanism

As Raj et al. [1988] have stated, the adhesion mechanism can occur in several different ways: as a covalent bonding, polymer chain entanglement or strong secondary interaction. The coupling occurs solely on the surface of the material and therefore it is important how the functional groups are delivered to the surface. Different bonding methods can occur simultaneously between two different substrates [Oksman Niska et al. 2008].

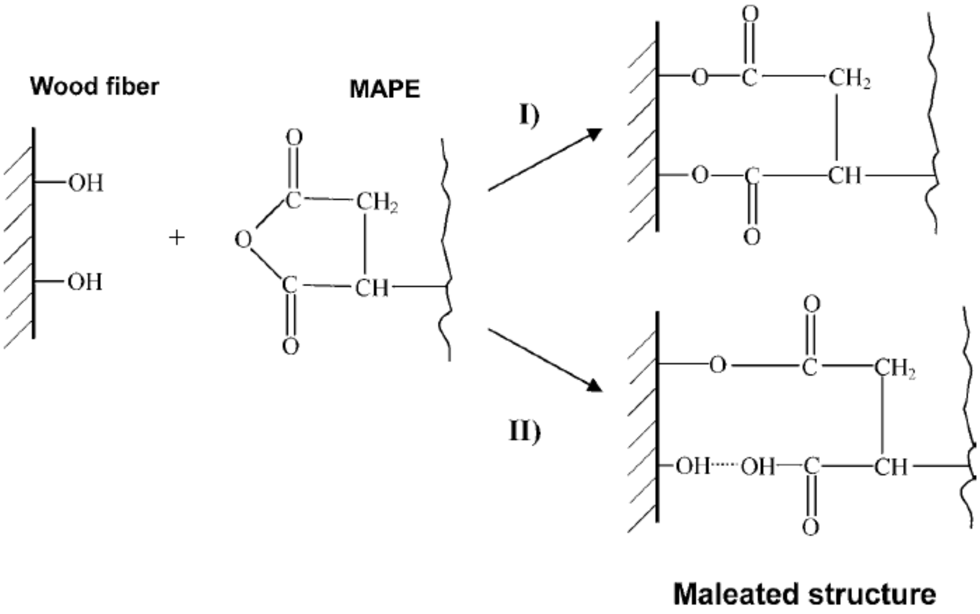

Figure 12 Hypotherical grafting structure at the interface of maleated wood-fibre/HDPE composites. (I) Succinic bridge structure and (II) half succine bridge structure. [Lu et al. 2005b]

Covalent bonding is presented in the Figure 12. Covalent bonding occurs when the OH-groups in the wood material react with a reactive group in the polymer (or polymer treated with coupling agent) to form a covalent bond with a strong interaction between two molecules. How strong the interface is, depends on the type of the bonds and their quantity. [Oksman Niska et al. 2008] However the covalent bond is the strongest compared to the other bonding mechanism, which are reviewed later in this section.

There are several electrostatic bonds, whose intensity depends on the type of the bond. The types of the bonds are e.g. ionic, hydrogen and dipole-dipole bonding. These different types of bonds are not equally strong. Like in covalent bonding, also in electrostatic bonds the strength of the interface depends on the type of the bond and the number of the bonds. [Oksman Niska et al. 2008] Electrostatic bonds are weaker than the covalent bonds. An example of electrostatic bond is presented in Figure 12. In the mechanical bonding the adhesion is caused by a friction between two separate interfaces. It can also be called as a mechanical interlocking, which may better explain the behaviour. The mechanical stress transfer can be high, but there is poor if any resistance against the water absorption as the reactive OH-groups are still available for water molecules. [Oksman Niska et al. 2008]

In the Figure 13 is shown interdiffusion. The interdiffusion is a state in which two types of molecules have entangled molecularly. It is sort of mechanical interlocking, but it occurs at the microscale, whereas mechanical bonding is more on the macroscale, as explained in the previous subsection. The entanglement happens through diffusion and occurs at the interface between two substrates, from which at least one has to be in a liquid state before curing. [Oksman Niska et al. 2008]

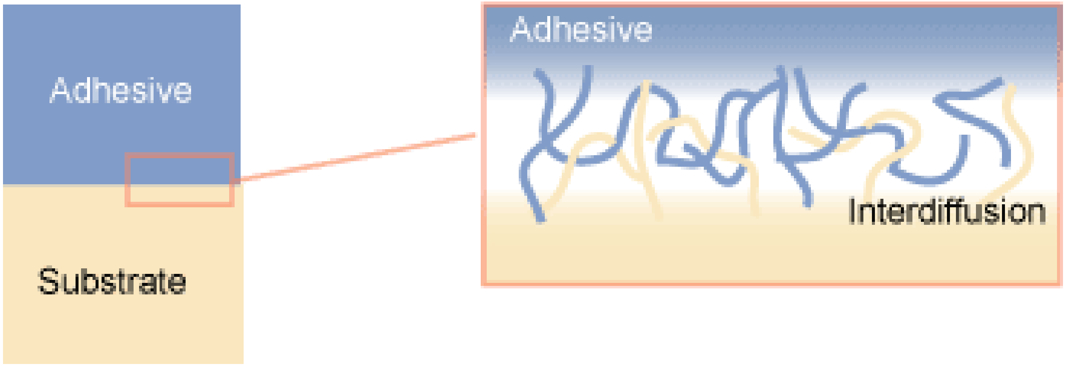

Figure 13 Demonstration of the interdiffusion [Special Chem webpage 2013]

As could be seen from the discussions above, there are several factors effecting on the properties of a wood based product, from the microstructure of wood material till the coupling agents enhancing the adhesion. Therefore it is important to design the process conditions to meet the requirements of the end product in the most efficient way as possible. In this research the focus is mostly on two different adhesive types: thermoplastic bonding and more conventional UF-bonding.

3 MATERIALS AND METHODS

The work was based on a composite product supplied by UPM in 2011. This material had undergone several years of development and was thus at present the most fully optimised material to date in plywood industry. These panels were then formed into “U” section profiles to simulate the form of a rotary die – a possible end use application of the new material. This represented a formed product.

The aim of the tests was to better understand the product and its behaviour. Therefore various tests were conducted with a lower amount of specimens.

Due to the broad nature of the tests, and the limited number of the test specimens and testing space/conditions, some of the tests were conducted with small amount of material. The tests having unexpected or interesting outcome, could be repeated afterwards at a larger scale on the company (UPM).

Nearly each test was conducted with comparable materials. These comparable samples varied according to their availability and the purpose of the test. While studying the formable, UPM Grada Plywood’s behaviour the comparable product was conventional urea formaldehyde (UF) bonded plywood, with birch veneers as in the Grada board. Whereas formed beech with conventional UF adhesive was selected as a comparable product for the formed Grada.

3.1 Material

One of the reasons for UPM to developed Grada was to enable post forming of plywood; another aim was to manufacture it using an environmentally friendly adhesive. Grada can be recycled at the end of the lifecycle, whereas traditional plywood is burned.

This thermoplastic formaldehyde-free glue turned out to have even more advantages, most of all: better moisture resistance, and somewhat equal strength properties, which were presumed to be lower than the ones of the conventional plywood.

The materials used in this work are summarized in Table 1.

3.1.1 Formed plywood: Grada and UF-bonded

There were three different materials used while studying the formed plywood: two thermoplastic bonded plywood (sanded and unsanded) manufactured by UPM, and a comparable product, bonded with urea formaldehyde resin (UF). All three materials were manufactured from nine (9) plies of 1.5mm veneer; however the wood species varied, as did the thickness of the plywood due to the sanding. Thermoplastic materials included the actual Grada (sanded formed Grada, marked as sample FG) and its variant (unsanded formed Grada, marked as sample UFG), manufactured from birch. To compare the behaviour of the formed Grada, the sole available comparable product was obtained from Italy. This comparison material was manufactured from beech veneers, which were bonded with UF. In the results section beech material was marked with the letters FB (formed beech). On this comparison material, some outside damage, presumably caused by the transportation, could be observed.

Thermoplastic bonded Grada -plywood: The target thickness of the actual Grada is 12.7mm. Though, the target is surpassed when using nine plies. Therefore the material is slightly sanded to attain the target value. Sanding is carried out before forming. The other thermoplastic bonded material used in the study is identical to the actual Grada described above, apart from sanding. The thickness of this unsanded material is slightly above 13mm. The manufacturing equipment is designed for the target thickness of the actual Grada of 12.7mm (+/- 0.1mm), therefore the uniformity of these two processes (for 12.7mm and above 13mm materials) could not be assured.

Another aspect to consider was the difference of the relative amount of wood between these formed samples. Sanding obviously decreases the relative amount of wood and therefore influences the moisture behaviour of the sample.

Comparable product: as reported above, the comparable product was manufactured by using beech. Even though beech and birch are both hardwoods, some divergence could be expected in their moisture. The fourth differentiating factor between the materials after wood species, bonding and thickness was the veneer orientation. Formed beech plywood had the surface veneers perpendicular to the veneer in Grada. In Grada, the grain direction in surface veneers was along the circumference, whereas in the formed beech the direction was perpendicular (see Figure 14 below).

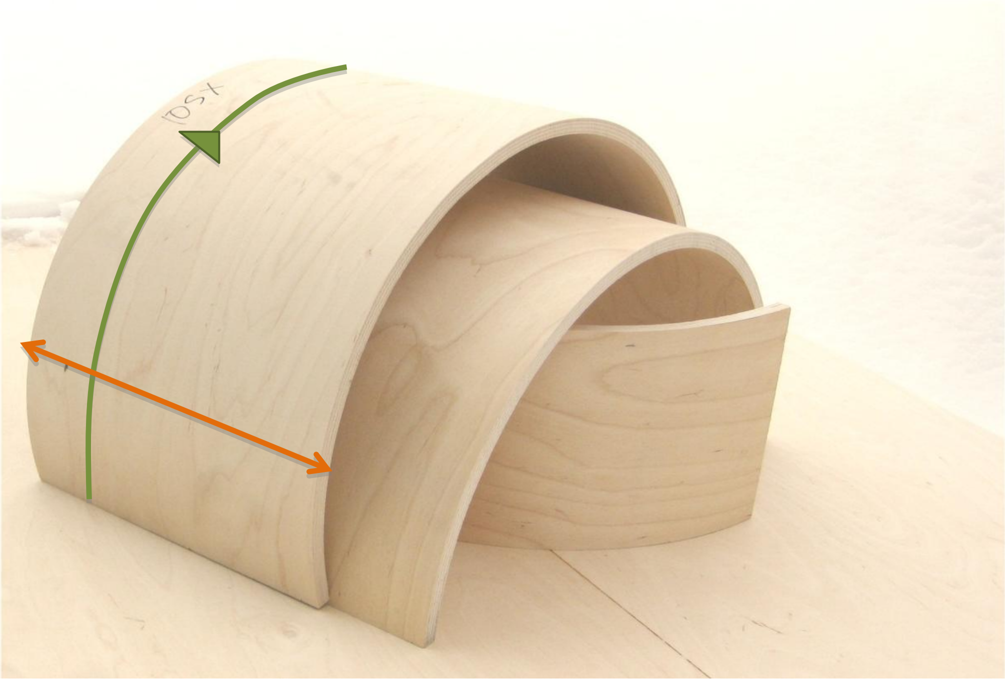

Figure 14 Grain direction of surface veneers in formed Grada (in green) and in UF bonded beech (in orange)

The final difference worth mentioning between actual Grada and the comparable material was the initial diameter, which was somewhat less in the comparable product, the average value was: actual Grada 483.03mm, unsanded Grada 482.563mm and UF-bonded beech 481.95mm.

Processing the test samples: the formed samples were sawn with a band saw at the Department of Civil and Structural Engineering in Aalto University. The sawing pattern can be seen in Figure 15 below.

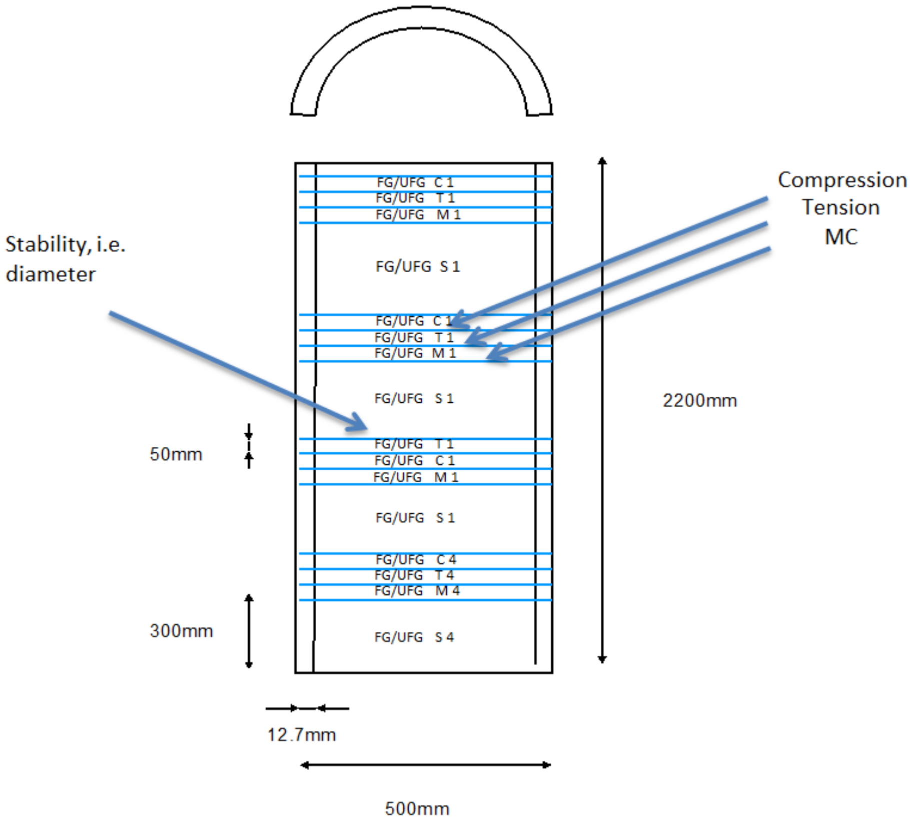

Figure 15 Sawing patterns for the formed samples. The largest specimen is for the diameter change test, MC-pieces are to study moisture movements in edge sealed specimens. Compression and tension specimens are for strength tests.

Concerning the amount of material, the length of the attained Grada-samples (sanded and unsanded) was equal, around 2.5m, whereas the comparable sample was almost one meter shorter. Because of this, in some tests the amount of the material was not sufficient to gather statistically valid results.

3.1.2 Flat material: formable Grada and conventional UF-plywood

The flat, formable Grada was manufactured from eleven (11) birch plies, of 1.5mm thickness, as in formed plywood, and had gone through the same sanding process as the formed one (formed actual Grada, FG). The conventional UF-bonded plywood (PW), serving as a comparable product, also had eleven (11) birch plies, though the surface layers were not sanded and therefore the relative amount of wood was higher. In addition to the differences in sanding, another property differentiated those two materials: initial moisture content. In Grada, the MC is lower. Is the lower MC due to the distinctive gluing process: thermoplastic glue does not include moisture as opposed to the conventional, liquid based UF bonding?

The flat test specimens were sawn from two plates of 1.0m*1.5m (see Figure 16). Saw kerf was intentionally overestimated to be 5mm to ensure that there was no lack of material. From Figure 16 can also be observed the grain direction, which is along the plate.

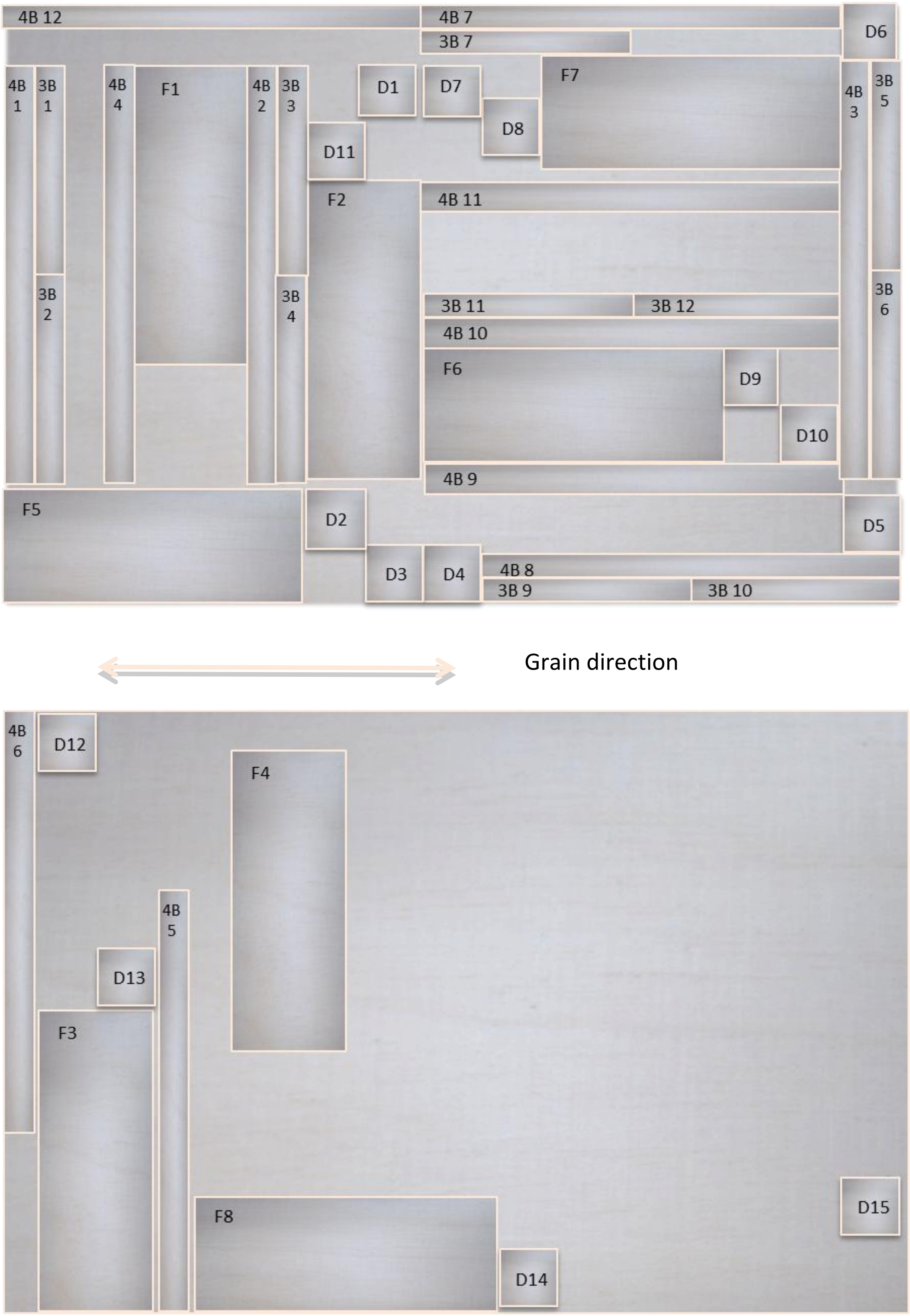

Figure 16 Sawing patterns of the flat samples (formable UPM Grada and UF bonded birch plywood). Specimens D1-15 were specimens to investigate moisture penetration through faces. F-specimens were sawn to study the flatness: F1-4 in crosswise and F5-8 in longitudinal direction). 3B and 4B specimens are for bending tests (1-6 in crosswise and 7-12 in longitudinal direction)

3.1.3 Special material manufactured by UPM

In addition to the above-mentioned materials, there was also a fourth thermoplastic bonded composite to study. A flat board in which raw material was identical to formable Grada's, with though fewer plies (9 instead of 11). The main difference between the materials was the orientation of the plies: in this specially made veneer composite, the plies were all in the same direction, not perpendicular to each other as in the others (Grada and conventional plywood) studied in the project. This new material was produced by UPM in order to learn more about the behaviour of the bonding. This material was used solely in one test (see Methods' subsection: 3.2.1.5. *Moisture penetration in specimen with plies in the same direction, in special thermoplastic material*).

Table 1 Properties of all materials used in the study

Properties	**Formed Grada (FG)**	**Formed Comparable (FB)**	**Formable Grada (G)**	**Formable Comparable (PW)**	**Special-made Grada (SM)**
Wood specie	Birch	Beech	Birch	Birch	Birch
Glue	Thermoplastic	UF	Thermoplastic	UF	Thermoplastic
Number of plies	9	9	11	11	7
Direction of plies	Cross structure	Cross structure	Cross structure	Cross structure	Oriented

3.2 Methods

The tests were carried out mainly at the laboratory facilities at the Department of Forest Products Technology at Aalto University, School of Chemical Technology, but also other Schools' facilities at Aalto University were exploited.

3.2.1 Stability of the product

The testing conditions, i.e. the cabins where the tests were carried out in, are introduced at the beginning of the stability section. Stability tests can be divided into two separate parts: the first part focuses on investigating the stability i.e. physical changes in form and dimensions. The second part consists of observing the moisture movements within the product. Tests were carried out on both, formable and formed materials.

3.2.1.1 Testing conditions

The stability tests were carried out in two climatic test cabins. The manufacturer of the cabins was Rubarth Apparate GmbH. In these climatic test cabins, both temperature and relative humidity (RH) were controlled in desired cycles. Table 2 summaries the characteristics of each cabin.

Table 2 Details of the cabins

Properties	Cabin 1	Cabin 2
Model	4201	4101
Volume	530l	350l
RH	30%, 50% and 80%	80%
Temperature	23°C	23°C
Number of weeks	11	3-6
Tests	• Moisture penetration in edge sealed specimens (formed and formable) • Diameter change (Grada) • Flatness	• Moisture penetration in ⇒ Surface sealed ⇒ Surface & edge sealed (3 of four edges sealed) ⇒ Special made thermoplastic plywood specimens • Diameter change (beech)

The cabin one was expected to more stable. The large volume of certain test specimens (especially in Diameter change test, 3.1.1) resulted in a lack of space in the cabins and some prioritising need to be done, thus the comparable product in the Diameter change test was left out of the cabin one. Instead it was placed in cabin two subsequently, when the cabin was released to our use, i.e. 19th August. The launch of the tests in the cabin one was already on the 28th of June, i.e. seven weeks earlier.

Conditions in cabin one were altered from 30% up till 80%, every third week, or second in the very beginning (see table 3). Initial relative humidity was 50%. After two weeks, the RH was raised up to 80%; these conditions were prevailed for three weeks. Third stage was at 30%, and after three weeks, RH was restored to 50% for a three weeks' period (see below). Due to the limited availability of cabin two the RH remained at 80% during the whole experiment, since at higher RH the results were expected to be more distinct. Concerning the temperature, it was constant, 23 °C, in both cabins during the tests.

Table 3 Relative humidity in weeks in cabin one (first row) and two (second row). Each number responds to each week. In cabin two some tests were ended after three weeks.

	Calendar Weeks and RH % in cabins one and two												
	26	27	28	29	30	31	32	33	34	35	36	37	38
Cabin 1	50%	50%	80%	80%	80%	30%	30%	30%	50%	50%	50%		
Cabin 2								80%	80%	80%	80%	80%	80%

Measurements were repeated three times a week (every 2nd or 3rd days). As the changes were presumed to be more pronounced during the first days after changing the RH, the measurement frequency was increased during the first 3-4 days after each change in conditions. During that period measurement was done daily.

Figure 17 Conditioning cabin one, specimens inside; from the first grill: edge sealed formed specimens, diameter change specimens, edge sealed formable and UF specimens, and in the bottom the flatness specimens

3.2.1.2 Stability of the formed product – Diameter change

Dimensional stability is crucial property in final product, so we investigated the rate of change in diameter relative to the changes in the surrounding environment (RH and temperature).

In order to clearly observe the diameter changes, the specimens were designed to be as wide as possible; however the limited space in conditioning cabins constrained the width of the specimens to be approximately 300mm. From the beginning of the test eight specimens were studied, four from each of the formed Gradas (sample FG and UFG). Three indicators were marked on each specimen (e.g. FG S 1). The first indicator was FG/UFG according to the material, sanded or unsanded. The second sign indicated the test (S=stability of the diameter); sign “S” was naturally constant throughout this test. The third sign told the specimen’s location in the large sample; specimens 1 and 4 were cut from the ends of the sample, whereas 2 and 3 were situated in the middle. Three measuring points were chosen and marked, diameter 1, 2 and 3 (see Figure 18).

The comparable specimens (UF-bonded beech, marked FB 1 and FB 2) were sawn from a smaller sample and afterwards placed in cabin 2 for three weeks, with constant conditions (RH 80%).

Measurement itself was conducted by using a large calliper (Mitutoyo, model CD-60, accuracy 0.01mm, and maximum value 600mm), measuring the inner diameter of the specimen. The samples were placed in controlled conditions in climatic test cabinets and the changes in diameter of sections of “U”-formed board were monitored in relation to the change in the surrounding relative humidity. As pointed out in the previous section, the initial diameter of the three samples varied slightly according to the material, being the largest in the actual Grada (FG) and smallest in the beech (FB).

Monitoring of the diameter was carried out at regular intervals, on Mondays, Tuesdays and Fridays, every 1-4 day. After changing conditions, measurements were conducted daily.

According to the previous experiments, the diameter variance in each specimen would be stronger in either end of the specimen, depending which end was placed on the ground. Therefore the specimens in this study were always placed in the same direction: diameter three against the grating, to ensure that the possible influence of the position was eliminated. Due to this arrangement, the diameter one and two were supposed to vary more, compared with diameter three.

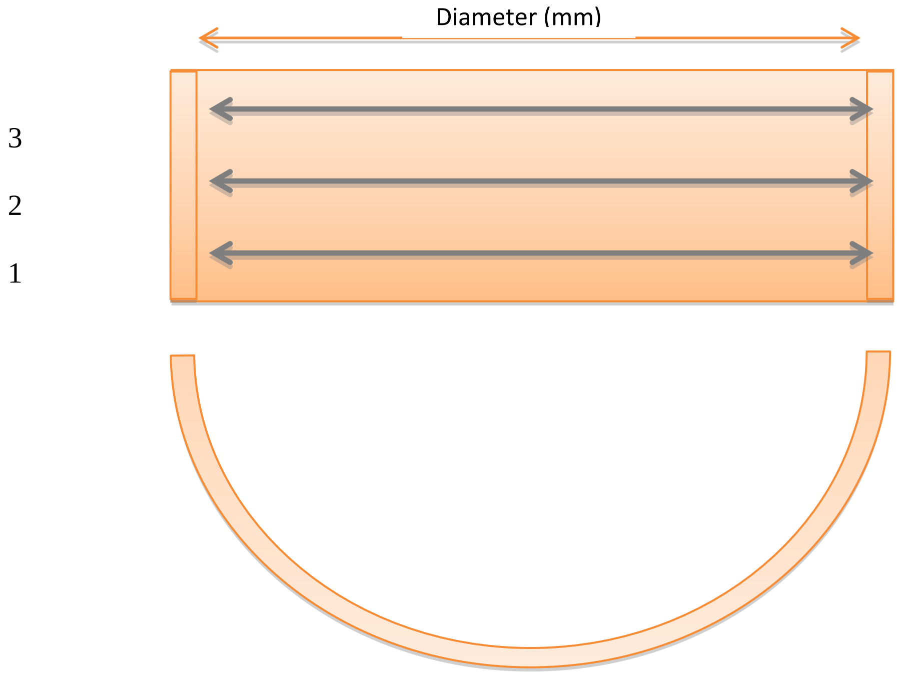

Figure 18 Measuring the stability, i.e. the diameter change of the formed product

3.2.1.3 Stability of the formable board: flatness of the flat surface

Previous (unpublished) research had indicated that the thermoplastic plywood might curve slightly more than conventional plywood. The aim of this task was to examine the “flatness” of the formable (G) board and changes that occur after changes in the ambient conditions (RH and temperature). UF bonded plywood was used as a control product.

The surface deflection of flat formable panels was measured relative to a flat surface after conditioning the board to differing RH (30, 50 and 80%). Specimens were cut so that the long side of the specimen was both perpendicular and along the grain direction, four specimens in each direction for each material, i.e. the number of specimens was (4+4+4+4) 16. The dimensions of the specimens were 500mm*190mm.

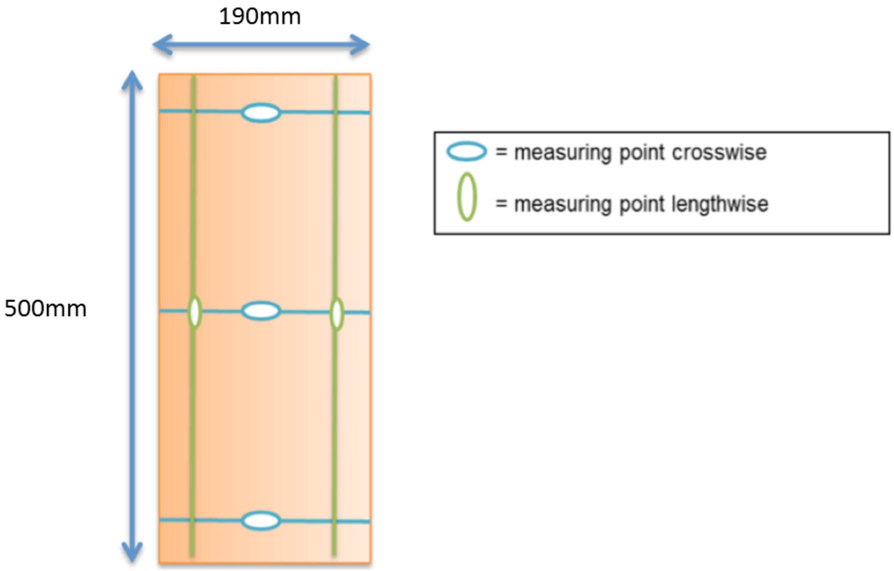

Figure 19 Flatness specimen - measuring points

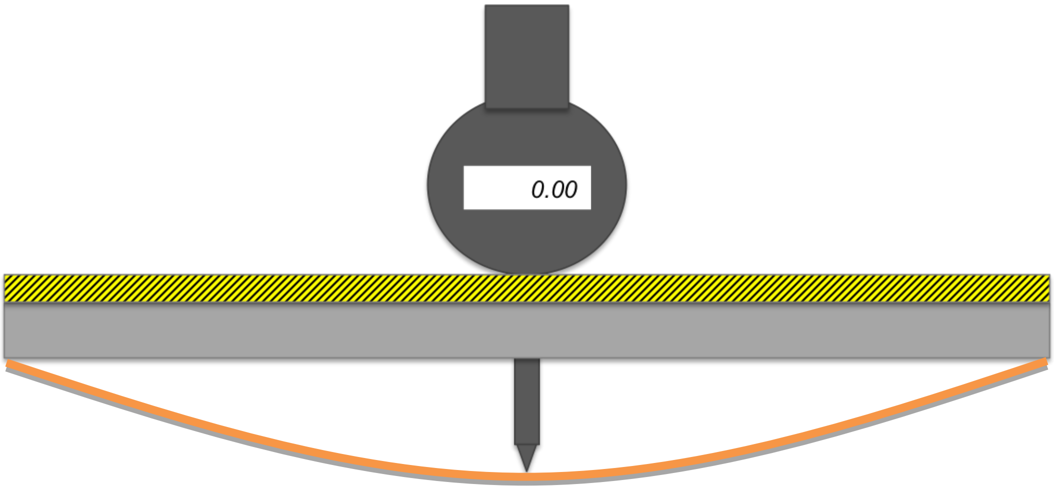

Figure 20 Dial gauge installed to the aluminium pipe to measure the flatness of the surface.

The test was conducted using a dial gauge (accuracy of 0.01mm) that was installed on an aluminium pipe (see Figure 20). The dial gauge measured the deflection of the specimen. The measurement was conducted at five different predetermined points (see Figure 19). Measuring intervals were identical to the previous tests.

From Figure 21 below can be observed how the measuring was conducted in both lengthwise (above) and crosswise (below).

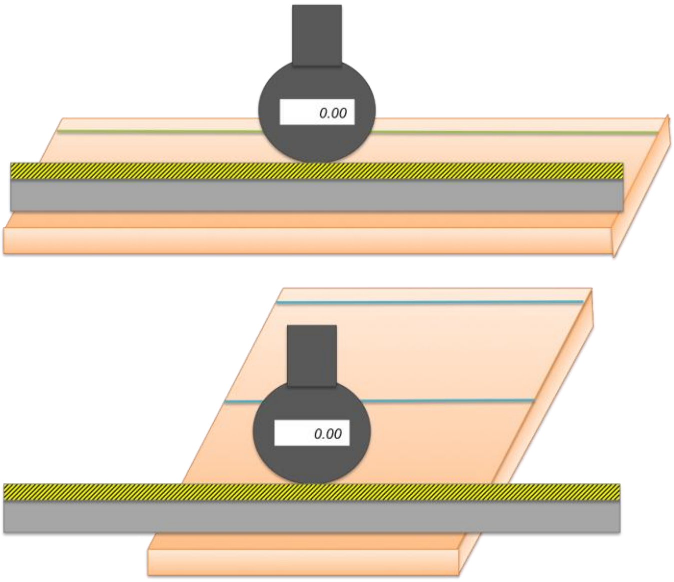

Figure 21 Measuring the flatness of the flat surface - lengthwise above and crosswise below

3.2.1.4 Moisture penetration and transportation through the surfaces

The aim of this task was to study to what extent the thermoplastic film acts as a moisture barrier. A high (or a low) moisture content in the surface veneers relative to the interior veneers may influence the properties (stability and strength) of the materials relative to comparable conventionally bonded plywood. The ability (or lack of it) of the internal veneers to absorb/desorb moisture may influence, for example, the moisture buffering capacity or the mechanical properties of the material. This task investigated the moisture transport phenomena in comparison to conventional UF bonded plywood. The task was divided into two separate parts: moisture movements through the surfaces of the formable product and then in the formed ones.

As mentioned in the Section 3.1.2, flat test specimens (G and PW) were sawn from larger plates (see Figure 16). The surface of the specimens was approximately 95mm*95mm. The amount of the specimens was 15 per sample, i.e. 30 in total.

The width of the formed specimens (actual Grada, unsanded Grada and UF-bonded beech) was 50mm (see the MC pieces on Figure 2), and the amount of specimens was four (4) per Grada sample (FG and UFG), and two for the beech, i.e. ten (10) in total.

Both formed and flat specimens' edges were sealed with aluminium tape to prevent moisture movements through them (see Figure 22 for G and PW, and Figure 23 for formed plywood). After sealing, the initial mass was recorded and specimens were placed in cabin one at a controlled temperature, 23 °C, and humidity. Mass changes in edge sealed samples were monitored as the boards were subjected to changes in relative humidity. Measuring intervals corresponded to the previous tests (Mon, Wed, Fri; after changing conditions, measurements were conducted more frequently).

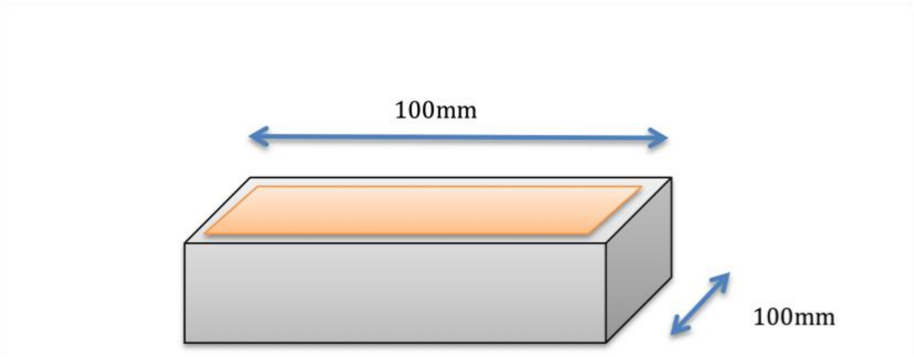

Figure 22 Moisture penetration in edge sealed specimens, formable Grada and UF-bonded beech

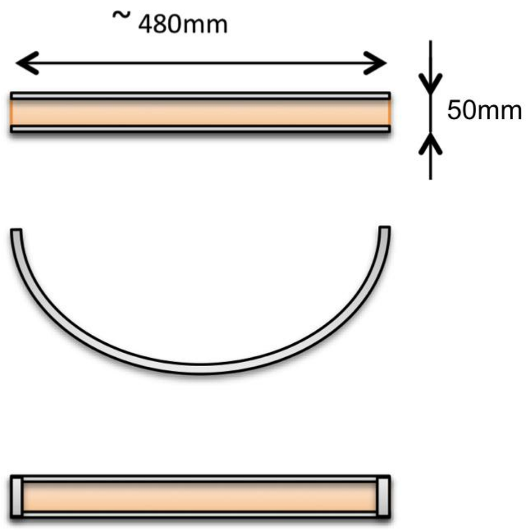

Figure 23 Moisture penetration in edge sealed specimens, formed Grada and UF-bonded beech

At the end of the experiment, after doing final measurements, the specimens were oven-dried to obtain the moisture contents throughout the test. The equation to calculate the moisture content can be seen below (Equation 1). The data was analysed to highlight differences in the moisture transport processes between the new product and conventional panels.

$$u = \frac{m_g - m_0}{m_0} \times 100 \qquad (2)$$

, where

u = moisture content (%)
m_g = mass at time of measurement
m_0 = oven-dry mass of the wood

Previous unpublished research indicated that the glue-line appears to act as a moisture barrier within certain limits. Therefore the moisture movements through faces should be stronger in PW-specimens, where the thermoplastic film does not hinder the moisture movements.

3.2.1.5 Moisture penetration through edges

After attaining some of the results from cabin one, other interests were evoked. A hint of the way in which moisture moves through faces had been found, but new questions arose: does the bonding affect the behaviour in other directions too; does the adhesive penetrate further into the veneer?

A few distinctive approaches were decided upon: in the first test the penetration through all edges in different thickness/side length –ratio was investigated. Surfaces were sealed and all the edges were left open to study the penetration through them. The second test was to investigate how the moisture penetrates through the specimen if only one edge remains unsealed. In the third experiment the special sample that UPM had prepared (see the end of Material section) was used. In this third test, the specimens were sealed as in the above mentioned, i.e. only one edge unsealed. However due to the special construction of the board, no comparison was done with UF-bonded material. Moisture penetration in both directions was examined: along and perpendicular to the grain direction. At the end, the aluminium tape was removed and all specimens were sawn into smaller pieces and oven-dried to obtain a MC map within each piece.

Moisture penetration through all (four) edges

Moisture penetration through four edges was tested to detect whether the influence of the thermoplastic bonding is extended deeper into the veneers. If bonding does not act as a moisture barrier in the horizontal direction, the moisture absorption is expected to be noticeable through edges, due to the properties of wood material (see Literature review).

In addition to the penetration direction, the aim in this test was also to study the effect of the specimen’s dimensions: whether the relation of side length to the thickness of the specimen has an effect on the absorption rate, as discovered in the literature. The thickness of the samples was constant, thus three different side lengths were selected:

50mm, 100mm and 150mm; two specimens per each size and each material (G and PW), i.e. six specimens per material. Specimens were weighted at the same intervals as all the other specimens (every 1-4 days). To prevent the effect of the surrounding conditions (unequal humidity) while monitoring the masses, the smallest specimens (50mm) were weighted first.

Figure 24 Penetration through all edges

As mentioned at the beginning of the subsection, the aluminium tape was removed and the specimens were sawn into smaller pieces at the end. The two largest samples (side lengths 150mm and 100mm) were sawn into 16 pieces (4x4). The smallest specimens (50mm) were sawn into nine pieces (see Figure 25). These pieces were then oven-dried to assess the moisture distribution within each specimen.

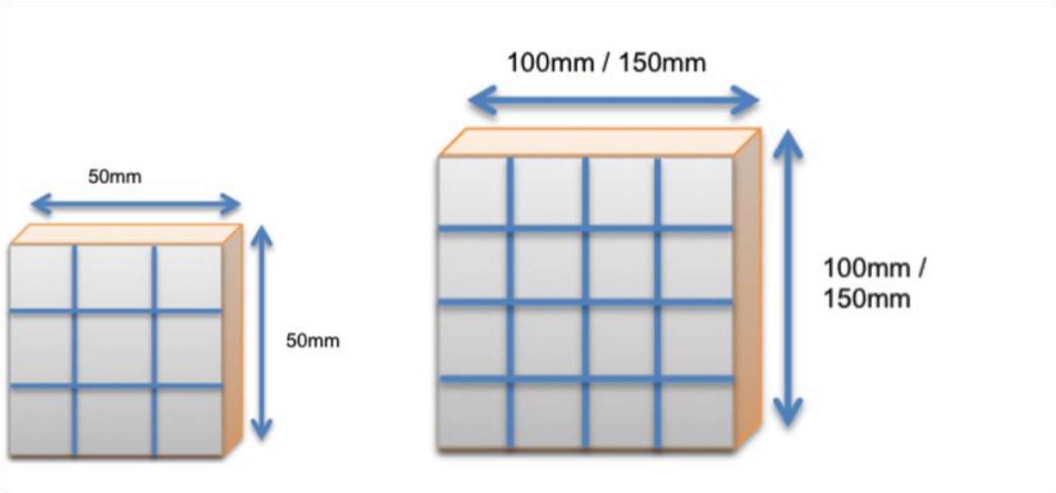

Figure 25 Sawing pattern of the test specimens to obtain their moisture maps

Moisture penetration and transportation through one edge

Moisture penetration in formable Grada

In the task above, the influence of open edges was studied. The idea was further extended: what is the influence of one single edge, how does the moisture penetrate through only one edge? Two specimens were sawn from both materials: G and PW. The dimensions of the specimens were 50mm*300mm. Due to the shortage of the material, the surface veneers' directions were not identical: in Grada, the grain direction in surface veneers was perpendicular to the lengthwise direction; whereas in the comparable product the direction was in the longitudinal direction (this was taken into account in the Results section). Sealed Specimens were placed in cabin two (i.e. RH 80%

and 23 °C) for six weeks and masses were monitored during the experiment as in the previous tests. At the end, the aluminium tape was removed and the specimens were sawn into smaller sections (see Figure 26 below) and oven-dried to map the moisture content inside the specimen.

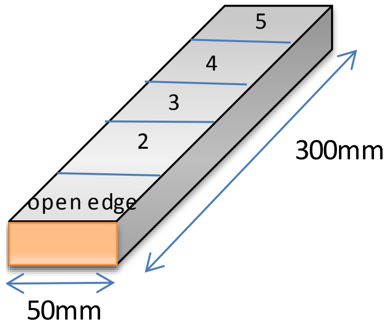

Figure 26 Moisture penetration through one edge, including sawing pattern

Moisture penetration in specimen with plies in the same direction, in special thermoplastic material

The special fabricated thermoplastic veneer composite was sawn into four specimens in total (100mm*200mm), to investigate the behaviour in both directions: perpendicular and parallel to the grain direction, two specimens per sample. The surfaces were sealed as well as all the edges, excluding one (see Figure 27 below). Specimens were placed in cabin two at RH 80%. Masses were monitored at identical intervals to the previous ones.

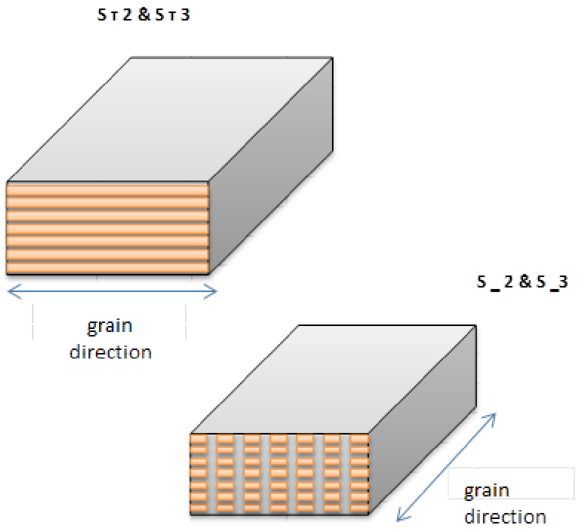

Figure 27 Moisture penetration through one edge - veneers in same direction

This was the final test concerning the moisture behaviour of the materials. Table 4 summarises the specimens used and tests carried out to investigate moisture transportation and dimensional stability. In the next section the strength properties of G and PW are introduced.

Table 4 The properties of the stability tests' specimens

Test (sign)	*Specimens (number of pieces)*	*Comparable (pieces)*	*Dimensions (mm)*	*Number of plies*	*Cabin*	*NOTE*
Diameter change (S)	*Formed (4 + 4)*	*UF beech (2)*	*50 (width)*	*9*	*1 (beech in cabin 2)*	
Flatness (F)	*Formable (16)*	*UF birch (16)*	*190*500*	*11*	*1*	
Edge sealed (M)	*Formed (4 + 4) & formable (15)*	*UF beech (2)* *UF birch (15)*	*50 (width)* *100*100*	*9* *11*	*1*	
Surface sealed	*Formable (3x2=6)*	*UF birch (3x2=6)*	*50*50* *100*100* *150*150*	*11*	*2*	
One edge open - Grada	*Formable (2)*	*UF-birch (2)*	*50*300*	*11*	*2*	*Surface veneers in different direction*
One edge open – special material	*Modified formable (2 + 2)*	*None*	*100*200*		*2*	*All veneers in same direction*

3.2.2 Strength properties of the product

Is Grada actually more “flexible”, “tough” or “resilient” than the conventional plywood?

In previous unpublished researches, some surprising indications were found: the strength properties of the UPM Grada Plywood were similar to the conventional UF-bonded board. No strong divergence had been found. In certain cases the polymer-glued thermoplastic plywood attained even higher values than the phenolic one. Besides, the quality of “flexibility” is an important factor in the marketing of the formable product. Therefore this aspect was investigated in particular.

The strength properties of both formable and formed Gradas were analysed. G was studied through three and four-point bending tests; within both of these tests UF-bonded birch plywood (PW, manufactured at UPM) were used as a control product.

Concerning the determination of the strength properties of the formed product, all three formed materials were studied: actual sanded formed Grada (FG), unsanded formed Grada (sample UFG); comparable material was formed UF-bonded beech (FB). When it comes to the methods, in compression and tension tests, a particular method was developed due to lack of convenient standards.

All the tests were conducted after conditioning, as requested in the standards. Mechanical behaviour was analysed and compared with the UF-bonded materials, PW. Load-deflection/stress-strain curves obtained in the tests were further analysed and comparison between materials was done. The intention was to investigate how Grada behaves, and especially how the behaviour differs from the conventional material.

The moisture content was naturally taken into account while calculating the test results, since it (MC) often has an effect on the strength properties.

3.2.2.1 Three and four-point bending

Mechanical tests were conducted according to the relevant EN standards. In the bending tests twelve specimens were chosen for each test sample (three- and four-point bending for both PW and Grada boards), six specimens were perpendicular to the grain direction and six specimens in the grain direction (see Figure 16 in Material section 3.1.2). Specimens were conditioned as the standards require at RH 65%, 20°C.

In case the samples would not attain approximately the same MC, the values could be multiplied to achieve unified results. For instance, to unify MOE values of two samples of MC 9 and 15%, the values at MC 9% should be multiplied with 1.1 to attain the corresponding MOE at MC 15%. [Veistinen et al. 1999]

Equipment utilized in the test was Zwick 1475 testing machine combined with MTS Premium Elite controller.

Three-point bending

The three-point bending test was conducted according to EN 310 (*Wood-based panels. Determination of modulus of elasticity in bending and of bending strength*) with a span of 300mm. The speed of the load was applied at constant rate: 0.01mm/min Length of the specimen was 350mm and width 50mm; thickness was naturally the actual thickness of the material. Modulus elasticity was calculated according to the standard. Other results are shown in graphs presenting load-deflection curves.

Four-point bending

The four-point bending test was carried out according to standard EN 408 (*Timber structures. Structural timber and glued laminated timber. Determination of some physical and mechanical properties*). Due to the deficiencies in the available equipment and programs, the parameters were slightly changed: the upper span was 230mm instead of 300mm and lower span 598mm instead of 780mm. The values were relative to each other and therefore testing errors should be diminished. The speed of the load was at constant rate: 0.0015mm/min. The length of the specimen was 600mm and width 50mm.

3.2.2.2 *Compression and tension of the "U"-formed board*

No apparent standards were found for the purpose of either compression or tension tests. Therefore slight adaptation was done. Above all, new holders were manufactured (see Figure 28 below) to hold the specimens still. The gap between the teeth in one holder was designed according to the thickness of the formed plywood, i.e. approximately 12.7mm. Large bolts were installed to hold the specimen still. Holders were attached to the Zwick (see Figure 29 below). The speed to break the specimens, i.e. loading and stretching, was 0.3mm/min.

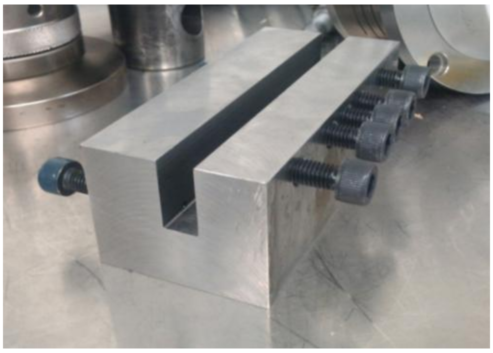

Figure 28 Holder for compression and tension tests

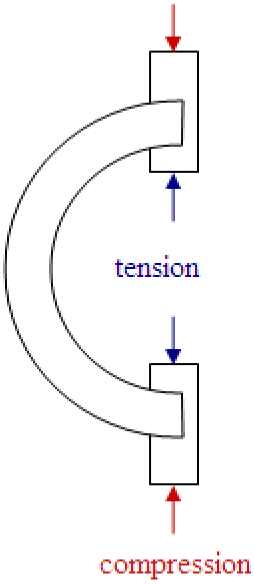

Figure 29 Compression and tension of the formed product

Results were expressed through the maximum load, and load-time curves, describing the behaviour of the materials.

3.2.2.3 Charpy Impact test (high strain rate)

The final test carried out in this research was a Charpy impact test. Even though the test is primarily used to study the properties of plastics and metals, in this project the test was presumed to provide some information concerning the behaviour of the product.

Tests were conducted with the respect of the standard EN-ISO 179-1 (*Plastics. Determination of Charpy impact properties. Part 1: Non-instrumented impact test (ISO 179-1:2010)*). The intention was to understand the behaviour of both the formable and formed Gradas. PW was a peer product. The instructions of the standard were slightly modified due to the thickness of the specimen, which was higher than recommended. The standard requires the width to be equal or larger than the thickness, thus to prevent the possible negative effects of the excess thickness, the specimens' width was sawn to be equal with the thickness. Plywood was categorised into long-fibre-reinforced composite materials, thus the specimens were left un-notched.

The impact test was carried out in the department of Engineering Design and Production, in Otaniemi. Device, Charpy Impact Tester, released a large hammer that broke the specimen. Two holders were attached to the specimen, the span between the supports being 40mm. The device measured the amount of stress that was required to break the sample. The capacity of the equipment was 300J. The influence of air resistance was taken into account and diminished from the value subsequently.

After obtaining the energy used, the impact strength was calculated by utilising the following equation (for un-notched specimens):

$$a_{cU} = \frac{E_c}{h \times b} \times 10^3 \tag{3}$$

, where

a_{cU}	is the Charpy impact strength of un-notched specimens (in kJ/m^2)
E_c	is the energy absorbed by breaking the specimen (in joules)
h	is the thickness of the test specimen (in millimetres)
b	is the width of the test specimen (in millimetres)

Tests were carried out in both directions: the blow in edgewise and flatwise directions (see Figure 30).

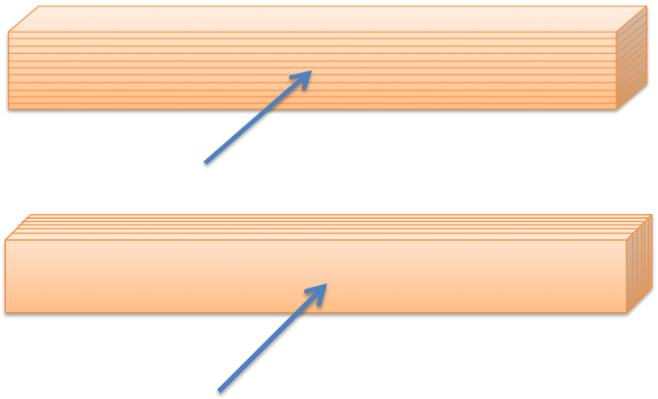

Figure 30 Impact test, blow's direction: edgewise (above) and flatwise direction (below)

Since the test had to be modified, the values are not comparable with literature. Though the aim was to compare the behaviour of the thermoplastic Grada with the conventional plywood and therefore comparable values from literature were not relevant. No clear divergence was expected between the materials.

4 RESULTS AND DISCUSSION

The behaviour of the product, UPM Grada, was studied in both stages: prior to and subsequent to the forming process. The tests were divided into two separate parts: first, moisture behaviour (i.e. stability) of the product and secondly its strength properties. The first part was seemingly larger, the amount and the magnitude of the tests was wider. Concerning the second part, the amount of tests was lower, but still, a strong difference in the behaviour of the materials was observed.

Before revealing the test results, some challenges that occurred during the testing are reported, to ease the reader’s understanding through the results and analyses.

First the moisture content of the samples: the overall moisture content of Grada was lower, which can be presumed to strongly affect the behaviour of the product due to the nature of wood material, depending firmly on the actual MC. But due to the enhanced moisture resistance properties of Grada, it would have taken an excessive time to condition the samples to the same MC, which was not possible in the time frame of this project. It would have been interesting to compare the behaviour of the materials (Grada and conventional plywood) within the same moisture content though.

When it comes to the equipment used in the Stability tests, every time the measurements were conducted, were also the conditions observed in both Climatic Test Cabins. As expected, in cabin one the conditions were essentially constant and in cabin two the variance seemed more apparent. In the latter, the relative humidity varied up to two percentage points, whereas in cabin one the variance was less than 0.5 percentage points. In addition, during the measurements in cabin two, one larger change in the conditions was observed via the results. The MC of the majority of the specimens in cabin two decreased suddenly for one day, thus it appeared that the cabin had been out of order for some time (from a few hours to one day). This will be discussed more in Section 4.1.3.2, at the end of the stability tests.

4.1 Stability of the product

4.1.1 Stability of the form

4.1.1.1 Stability of the formed product – diameter change

As mentioned in the Material and Methods Section, the dimensional stability is a vital property of the terminal product. The surrounding conditions may vary substantially. It is, therefore, important to evaluate the dimensional changes in varying conditions. The rate of change in diameter was studied according to the changes in the surrounding environment (RH and temperature).

The stability of the beech appeared superior to the one of the thermoplastic bonded materials (FG and UFG). Beech’s diameter percentage change was below 0.50% even after being exposed for 28 days at RH 80%, whereas the thermoplastic bonded materials attained the values of 1.36% and 1.53% after 21 days at RH80% (and 13 days at RH50%).

While comparing the behaviour of Gradas with the beech sample, it should be remembered that the raw material was different. Another aspect to consider was the initial moisture content, which was much higher for beech, 8.41%. MC was only 5.1% in UFG and 4.8% in FG. Within certain limits the lower the MC is, the higher its capability to absorb moisture is. Below the FSP wood swells when its MC increases. If the overall moisture uptake of beech was inferior to Gradas', it might have explained the differences of the diameter changes and the effect of the stress could be left out. However, the beech absorbed even more moisture (the MCs of the samples will be studied more closely in Section 4.1.2.2.). Also the higher density of the beech should have resulted in clearer dimensional changes. Since the overall result was the contrary, it might be presumed that the direction of the plies influenced on the behaviour. As stated in the Subsection 2.2.2, the dimensional changes of wood are the strongest in the tangential direction and the smallest in the longitudinal direction. Other reasons behind this phenomenon cannot be derived, since the process (e.g. process temperatures) of the beech product could not be ensured.

The behaviour of the unsanded (UFG) and sanded (FG) Gradas seemed to be parallel throughout the test, with a few exceptions. At the beginning of the test, the behaviour of both thermoplastic materials was close to identical, the actual Grada's (FG) diameter attained slightly higher values though (difference between materials remained below 0.1%).

A larger divergence appeared after increasing the relative humidity (RH) up to 80%. The formed Grada (FG) surpassed the curve of the unsanded formed Grada (UFG), indicating a stronger absorption. However, after a few days, FG's absorption rate slowed down and meanwhile the UFG continued at the same pace, attaining the highest point of the percentage change.

A similar, but not as clear reaction emerged while decreasing the RH down to 30%. The FG attained lower values within the first two days, following with a slightly gentler curve, whereas the UFG continued approximately the same manner since the decrease of RH.

Between Gradas, the sole difference was the thickness of the surface veneers due to the sanding, moisture content being parallel. The slowdown of the stronger absorption of FG after a few days might have resulted from the lack of material for further penetration, whereas in the unsanded UFG there was still material into which the moisture was able to penetrate.

In addition to the small variances between FG and UFG, it also appeared that their inner variances diverged. Within FG, the averages of every specimen differed from 0.0 to 0.12%. For UFG, the variances were between 0.08 and 0.34% (see Table 5).

Table 5 Average diameter change (%) and variance within the sample

	Sample			
	FG		UFG	
RH (%)	Average (%)	σ^2	Average (%)	σ^2
50	0.17	0.001	0.15	0.003
80	0.82	0.003	1.13	0.020
30	-0.28	0.003	-0.43	0.015
50	0.21	0.000	0.18	0.001
Av		0.0018		0.0098

The behaviour of the actual Grada (FG) appeared to be slightly more pointed and meanwhile stable than the UFG. The variance is slender for FG (see Table 5). This more uniform behaviour was characteristic to FG throughout several tests, whereas UFG's behaviour varied more, resembling more the behaviour of a heterogeneous wood material. This was also expected since there was more substance above the first glue-line on UFG. This peculiar behaviour of FG will be discussed in the following sections.

When it comes into the effect of the position of the specimen in the conditioning cabin, no evidence of the direction could be shown. However, 300mm might not have been wide enough to observe any difference. If the influence should be proved, clearly larger specimens should be used. To be noted also that the grill of the cabin might have enhanced the ability of the ground end (diameter three) to move, since the circle touched the ground only in limited amount of spots.

4.1.1.2 *Stability of the formable board: flatness of the flat surface*

It was predicted that the changes in the specimens' form depend on the direction of the surface veneers. When the grain direction of the surface veneers was in the longitudinal direction of the specimen (specimens F5-F8, see Figure 16 and Figure 19), the surface topography differences should have been higher when measuring lengthwise, due to the nature of wood material and to the form of the specimen (crosswise length is clearly shorter than the lengthwise direction).

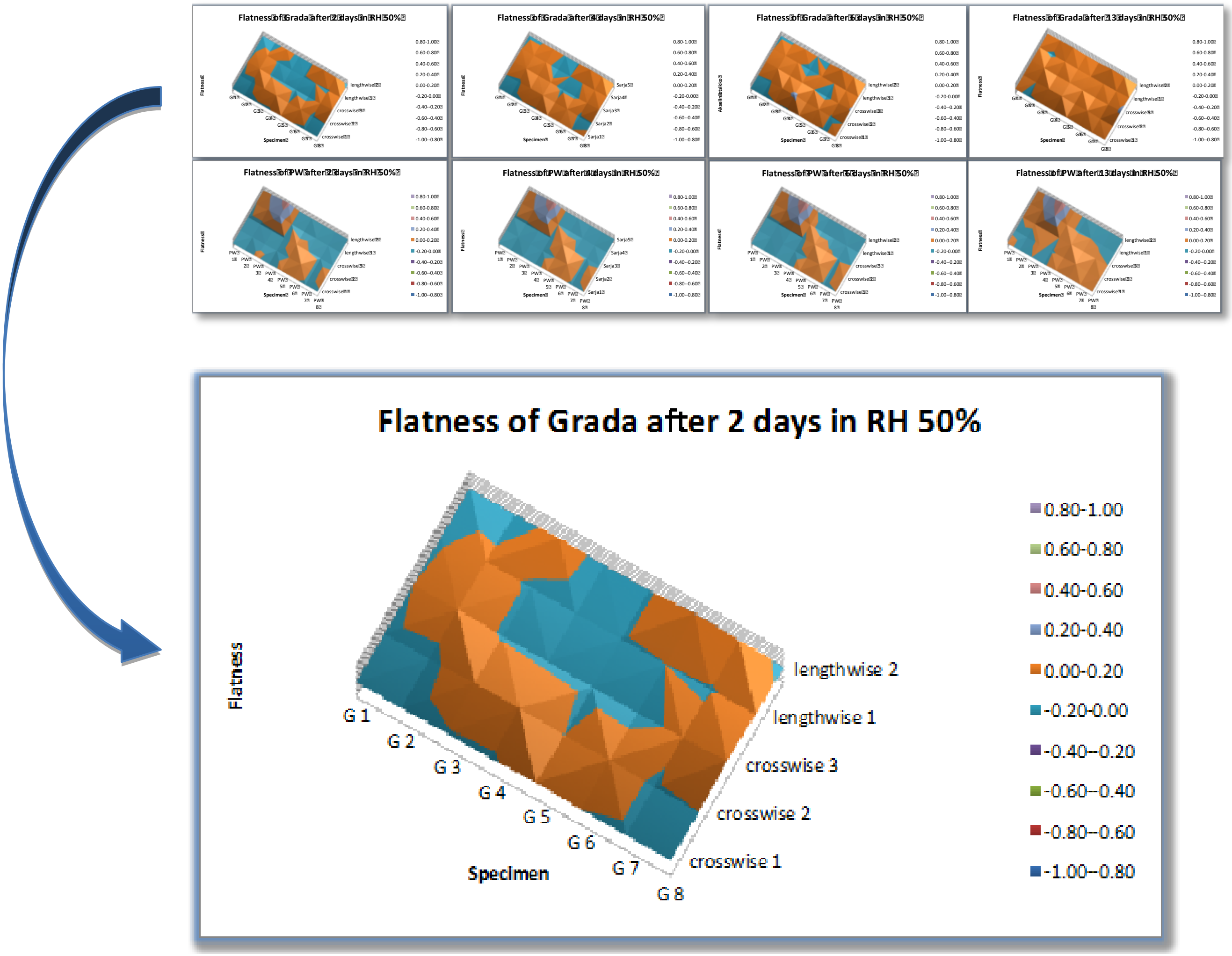

Figure 31 Flatness of the Grada (G, 1st row) and UF bonded plywood (PW, 2nd row) at RH 50% after 2, 4 6 and 13 days. Below is a magnification of the first graph. These figures are available in Appendix II.

When the samples were first put in RH50%, no clear divergence between the materials seemed to occur, in both materials, G (1st line) and PW (2ndline) the curvature varied from -0.20mm to +0.20mm (represented by yellow and blue colours, see Figure 31).

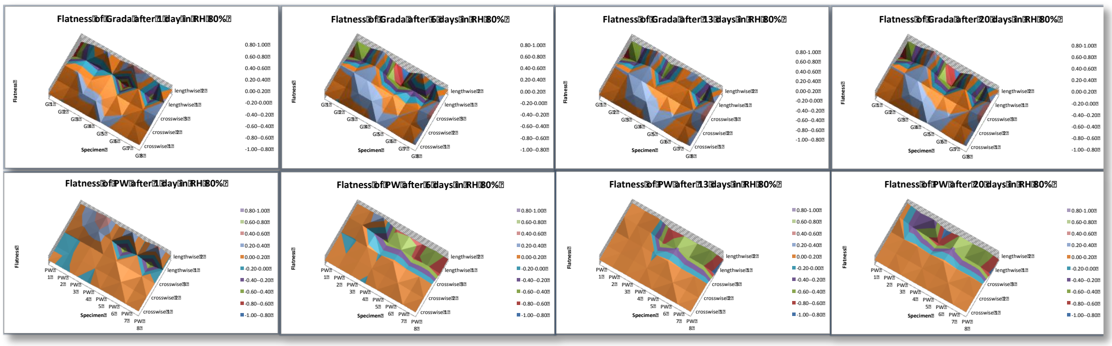

Figure 32 Flatness of G (1st row) and PW (2nd row) at RH80% after 1, 6, 13 and 20 days. These figures are available in Appendix II.

Stronger differences between the materials in the surface topography (G and PW) appeared after one week at RH80% (see Figure 32 above). Grada seemed to be slightly more sensitive to the surrounding condition changes: after the first 6 days its surface curvature was between -1.00mm and + 0.60mm, whereas for UF bonded plywood the surface topography remained between -0.80mm and +0.40mm. Overall during the RH80% phase there was more variation in G's surface topography, which can be seen from the wider colour range. In addition, in G the changes arose in both directions: lengthwise and crosswise (see Figure 19 in Chapter Materials and Methods), whereas in PW the differences remained mainly on the lengthwise side. Within both materials, the surface variations in the crosswise direction were not nearly as strong as in lengthwise, as presumed. The changes were believed to occur more in the lengthwise direction due to longer span in measurement, which intensifies the differences. Nevertheless, how did the materials behaviour change after decreasing the relative humidity?

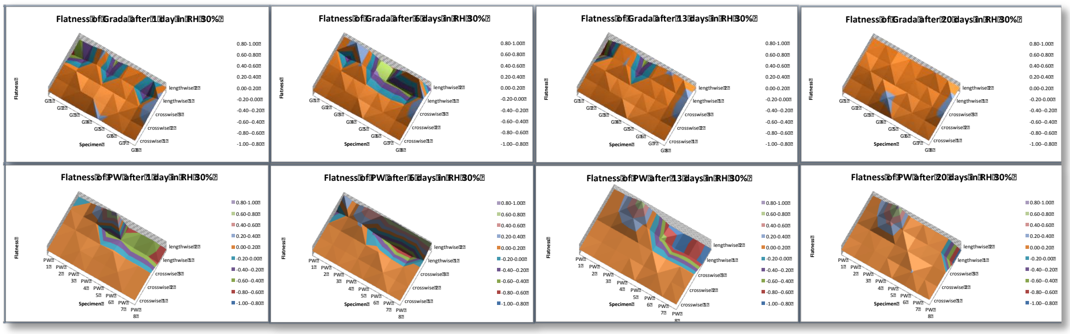

Figure 33 Flatness of G (1st row) and PW (2nd row) at RH30% after 1, 6, 13 and 20 days. These figures are available in Appendix II.

A distinction between the materials also arose when decreasing the RH down to 30%. The first day the curvature of G had distinctly diminished (surface topography from -

0.80mm to 0.4mm), whereas PW had had only a few minor changes, (topography staying between -0.8mm and 1.0mm, see Figure 33 above). After 6 days, some curvature rose up in Grada, but it had disappeared the 13th day. In PW the differences that had developed at RH80% were still quite strongly present after two weeks. The 20th day the surface topography of both samples was almost even. In G, there were minute spots of 0.20-0.40mm in three specimens (G3, G4 and G8). In PW, these distinguishable spots varied from the highest values to the lowest ones (-1.00-1.00mm) in four specimens (PW 1, PW 2, PW 3 and PW 8).

In G the surface grain direction did not have a strong influence; the topographic variances appeared within all specimens in all directions. In PW somewhat stronger variance could be observed within specimens PW5-PW8, where the grain direction was in the lengthwise directions.

There was one flaw in the test arrangement in the initial measurement, prior to conditioning. The measurements of the first day, before putting the samples to the test cabin, were not accurate due to a misunderstanding of the equipment. The error was detected and rectified for the next measurement. Therefore the first reliable values were after two days of conditioning (RH 50%). This was likely to have only a minor effect on the results, since prior to conditioning the boards were in a room where the temperature and humidity were somewhat similar to the first conditions in the cabin. And nevertheless, the same incorrect measurement had been conducted on both materials: Grada and the control specimen, i.e. UF bonded plywood.

The test specimens were sawn from larger plates, as discussed in the Material-Section. The middle part (1.5m*1m) of the large Grada board (1.5m*3m) was surplus. This surplus part was stored in a room with approximately constant conditions. At the end of the project when sawing the last test specimen (in the middle of October), considerable twisting of this part could be observed (see Figure 34 below). The Grada test specimens in the condition cabin twisted in the same manner as this larger plate.

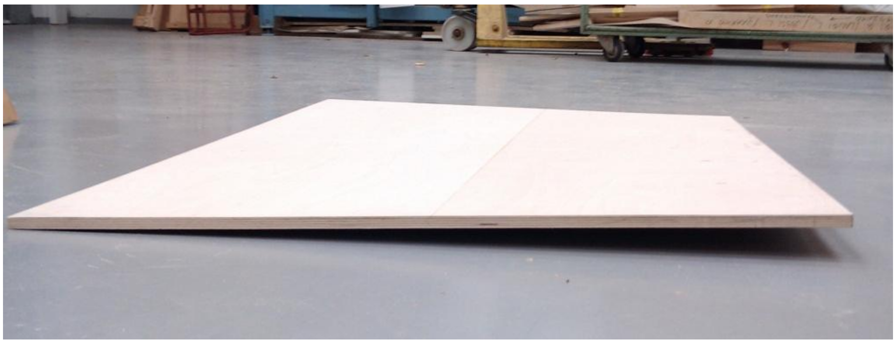

Figure 34 Twisted plate of UPM Grada Plywood

Throughout the test Grada reacted faster to the surrounding conditions (especially at RH80% and RH30%), but it seemed to recover more easily as well. In UF samples the changes seemed more permanent. In addition, a more composite-like behaviour could be detected on Grada, since its topography variances occurred in both directions and were not limited to the lengthwise direction, as in the conventional plywood.

While comparing the results with the previous one, in this test Grada seemed to continue the same behaviour: being reactive to the surrounding conditions. Due to a clearly lower initial moisture content of G, the surface veneers were expected to react more easily to the RH changes. In addition, the adhesive seemed to act somewhat like a moisture barrier, since the changes were fast and somewhat stabilised after the beginning; therefore it can be presumed that most of the changes occurred on the surface veneers.

The Flatness test could also have been conducted in a different way, positioning the test equipment (the aluminium pipe where the dial gauge was attached) apart from the specimen, and not laid on the specimen as it was implemented in this case. If the test equipment had been placed above the specimen, the larger twisting (as seen on the Figure 34) could have been observed more thoroughly.

4.1.2 Moisture penetration and transportation through the surfaces

4.1.2.1 Moisture transportation in flat, formable product

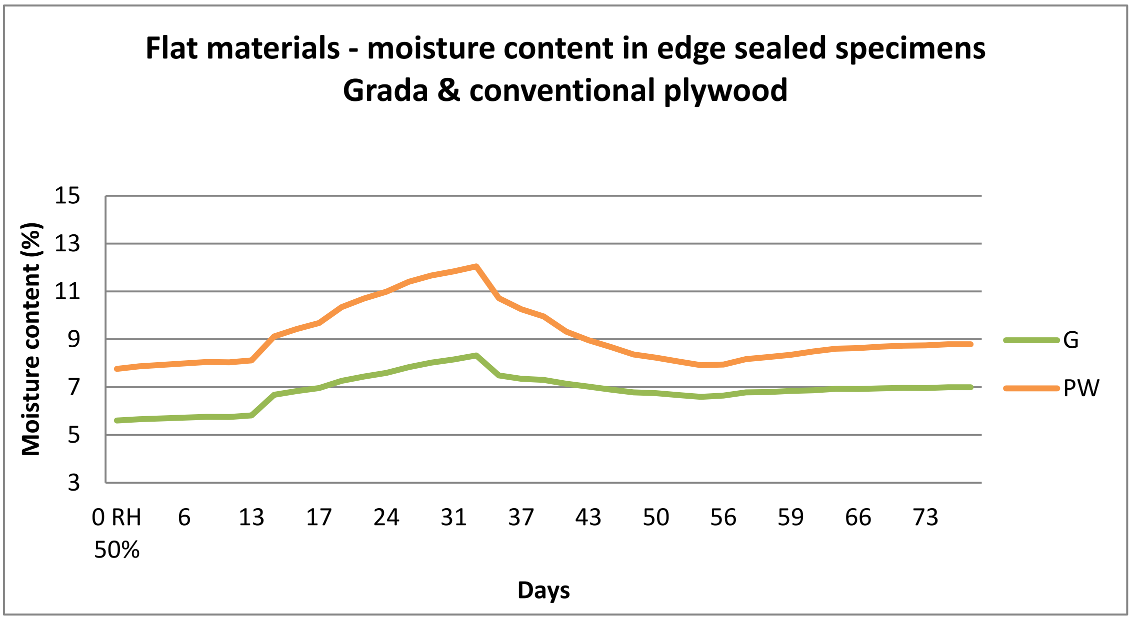

Figure 35 Moisture content in edge sealed flat specimens

From the Figure 37 above can be observed that there was a clear difference in the initial moisture contents of G and PW (5.6% vs. 7.76%). The difference remained throughout the entire test, but its magnitude varied, being the largest at the end of the period of RH80% and the least at the end of the period of RH30%. During the last experimental period of this test, at RH 50%, G appeared to stabilize around MC 7% and at PW around 9%; thus also the initial differences between the materials, seemed to endure more or less after the changes.

To have a more thorough view of the MC changes of two materials with such distinctive MCs, the development of the percentage MC differences was investigated as well. While studying the percentage differences, a more specific behaviour appeared (see Figure 36 below): the differences in Grada seemed more precipitous: both the absorbing and desorbing peaks were sharper for Grada and appeared within the first days after the condition changes; whereas for the conventionally bonded plywood, the changes were milder, but more long-lasting. This kind of behaviour also occurred in previous flatness test, and was presumably derived for the same reason: drier face veneers and the glue-line that hinders the moisture uptake further from the surface layers.

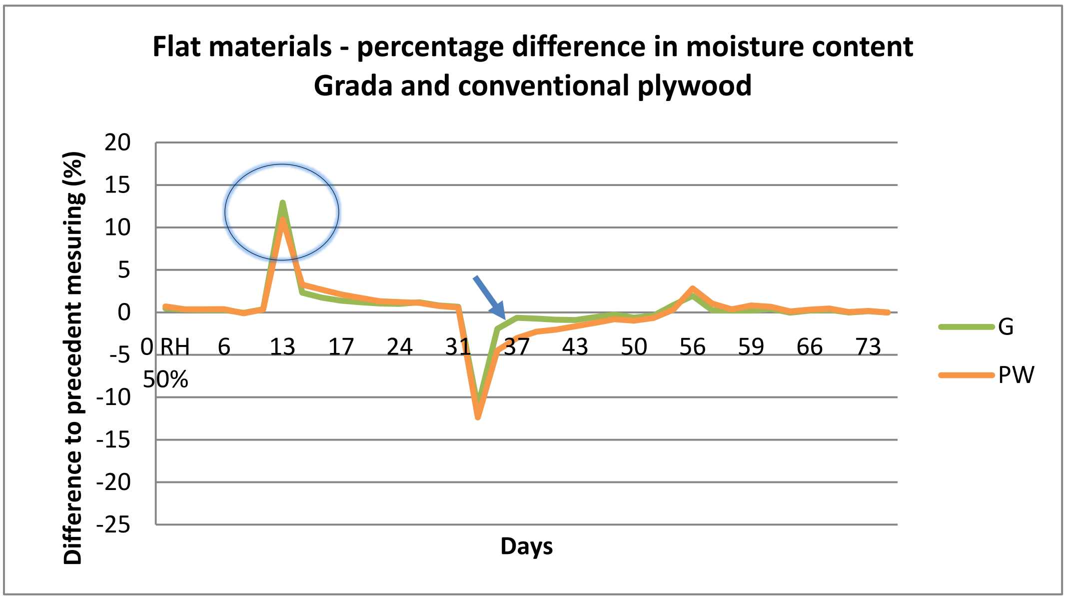

Figure 36 Flat materials, percentage difference in MC. Relative humidity was increased up to 80% after 14 days, decreased down to 30% on the 35th day and increased back to 50% on the 56th day.

The MC of PW varied from 7.76% to 12.04%, whereas G's MC remained between 5.6% and 8.32%. In the end, the percentage differences between the extremities were not far from each other though: 35.5% for PW and 32.7% for G. To conclude, the difference between the materials G and PW is Grada's reactive behaviour right after changing the conditions. This behaviour was restricted more or less to the surface veneers though.

4.1.2.2 Moisture transportation in formed product

Even though beech seemed stable in the Stability of the form - test (Section 4.1.1.1), variance seemed to be the opposite, when observing the moisture content of each material: formed UF-bonded beech absorbed much more moisture than Grada did.

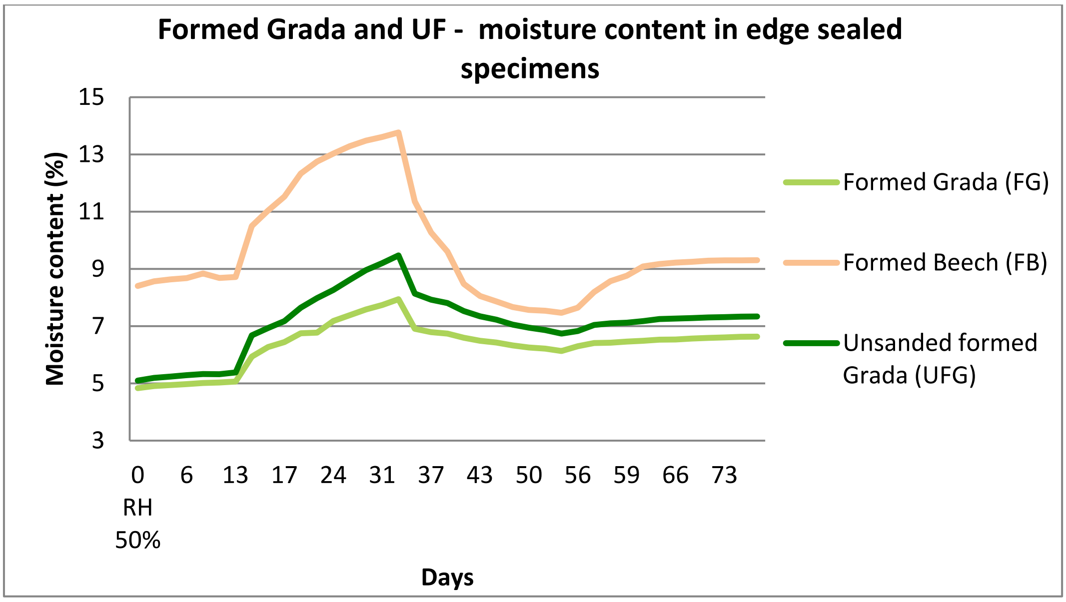

Figure 37 MC in edge sealed formed materials: Grada (actual FG and unsanded UFG) and formed beech plywood

Grada had seemingly lower values through the whole examination (see Figure 37). Although while RH was diminished down to 30%, the moisture content difference between the materials dropped down from 4-6% to slightly above 1%. After increasing the RH to 50% the moisture content difference widened to above 2%. As within the formable material, also within formed material the MC curve was stabilized at around 7% after lowering the RH from 80%. UF bonded beech stabilized after increasing the RH up to 50%, staying slightly above 9%.

When studying the percentage differences of the MC (see Figure 38 below), the formed Gradas (FG and UFG) appeared to behave in the same manner, differentiating from the formed beech.

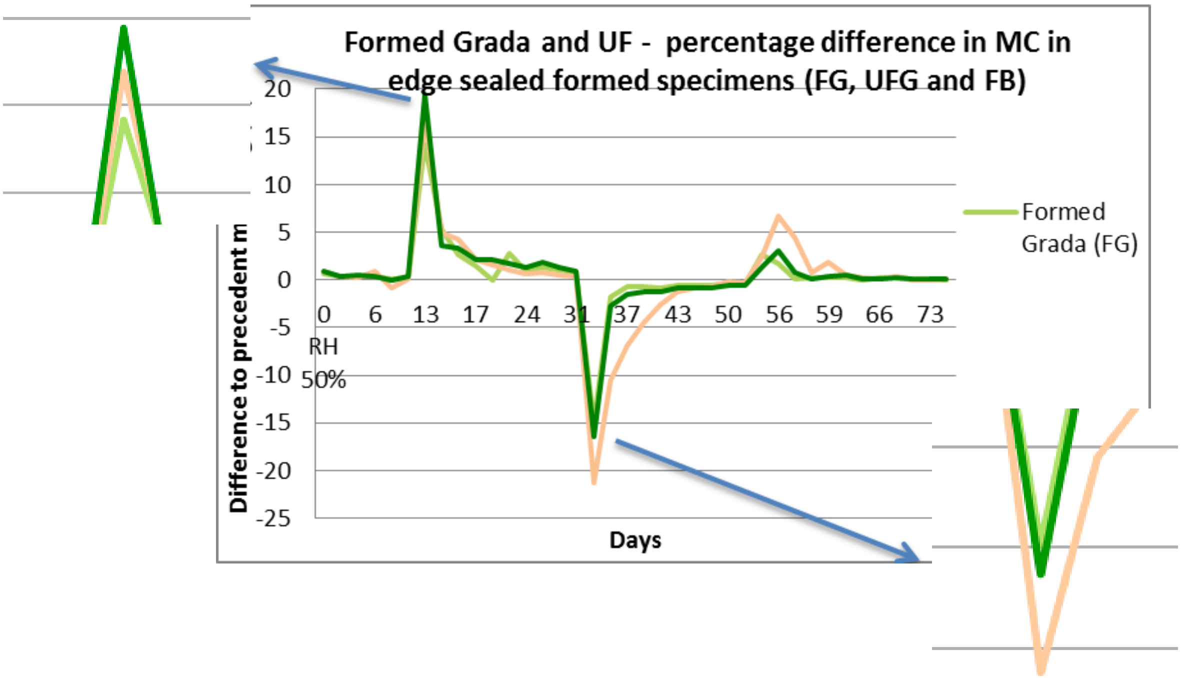

Figure 38 Percentage difference (%) in MC in formed edge sealed materials: FG, UFG and FB

The curves expressing percentage moisture content changes were sharper for Grada (FG and UFG) compared with UF bonded beech plywood, as in the previous test. However, all the volumes were larger for the FB than for FG. Between FG and UFG, no strong differences could be found. The sole outstanding variance between FG and UFG emerged in the first peak, right after increasing the RH up to 80%. The difference between FG and UFG was presumed to originate from thicker surface veneers since there was more substance into which moisture could absorb to before reaching the bond-line that hinders the absorption. UFG also surpassed FB at the first peak, which was most likely due to the clearly lower moisture content in the very beginning.

4.1.2.3 Moisture transportation in UF bonded and thermoplastic bonded materials (both flat and formed materials)

While comparing flat Grada (G) with the formed one (FG), a resemblance could be observed. The maximum MC for both materials was close to 8%, FG staying slightly lower. However, as can be observed from Figure 39 below, the moisture resistance of G was slightly higher than the one of FG, since its overall MC increase was somewhat more delicate.

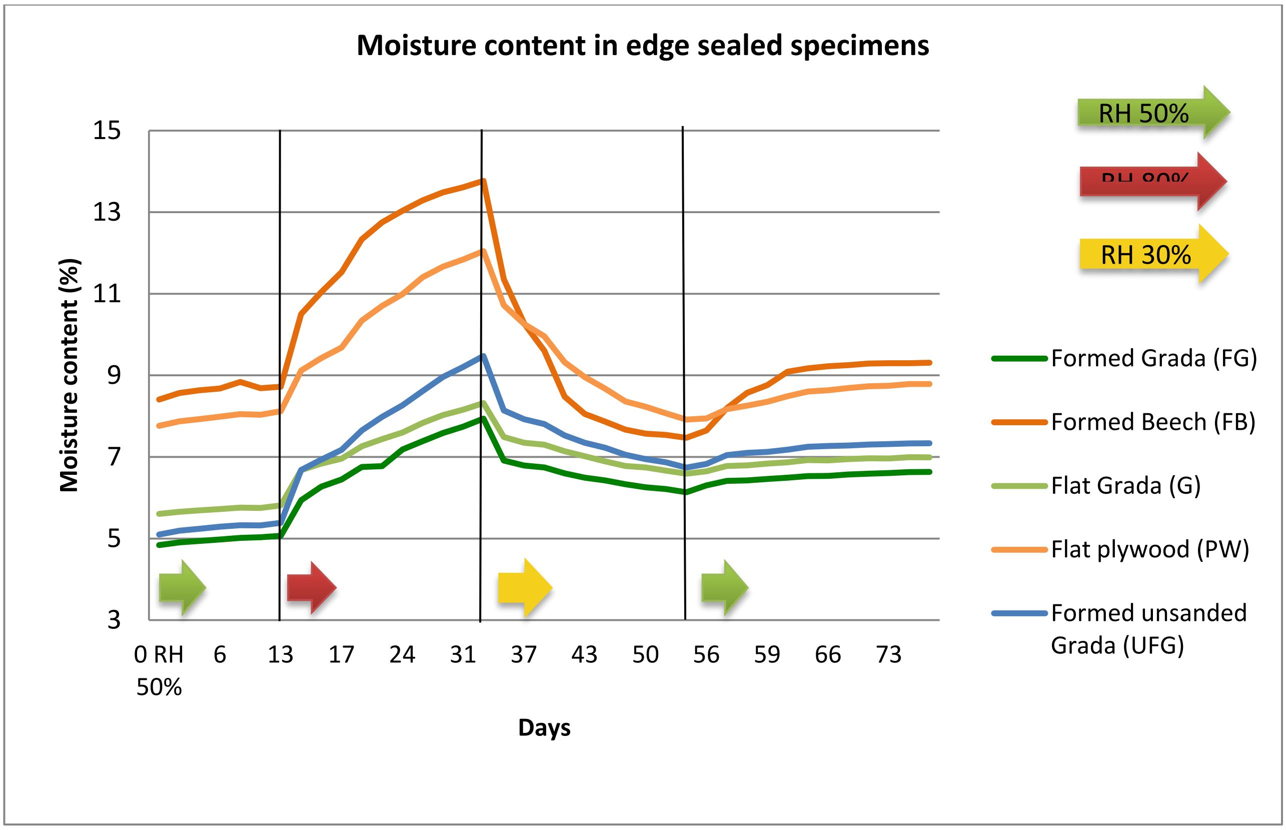

Figure 39 Moisture content of all the edge-sealed specimens

One surprising phenomenon appeared though; the flat Grada seemed more resistant to moisture absorption than the formed (unsanded and sanded) Grada. Due to the forming process, during which the inner temperature of the plate increases up to 130˚C, it was more or less expected that the reheating would have enhanced the moisture resistance, which appeared to be the contrary. Perhaps the following could explain the reason for this occurrence.

After monitoring the behaviour of the specimens in the cabin, the edge-sealed specimens were oven-dried (without removing the aluminium tape from the edges) to obtain the actual MC of the specimens. An unexpected phenomenon appeared: UFG specimens started to delaminate significantly. FG showed modest delamination as well, however clearly at a different scale. The melting point of the adhesive is approximately 130°C, whereas the temperature in oven drying was 103°C. The sole difference between FG and UFG was the thickness of the material: FG had been sanded to the target thickness of 12.7mm prior to forming.

In several cases the delamination occurred in every second plies (see Figure 40).

Figure 40 Delamination of the specimen 18 M 3 after oven-drying

In some specimens, the plywood had delaminated through almost the entire specimen. Within FG, only one specimen had slight delamination. The melting point of the bonding could not explain why only the specimens of UFG delaminated. Either the UFG had not been well formed due to too higher thickness, deriving to lower pressures during the forming, impairing the adhesion. Another explanation might have been the contrary: too much inner force derived in the process. A third alternative for the deterioration was the higher relative amount of wood material, absorbing moisture. The average moisture content of FG was 6.36% whereas for UFG the value was 7.12%. Thus, there was more moisture inside the UFG, trying to find its way out; the generated pressure might have caused the delamination. Besides, since the moisture could not desorb through the surfaces (as the glue-line appeared to act as a barrier to the moisture), it delaminated the material due to high inner pressures. The delamination occurred foremost in every second plies, which might have been derived from poor bonding quality due to lathe checks occurring mainly on the other side of the veneer. [DeVallance 2007]

Delamination occurred in flat formable specimens as well, but only in a very few ones, which were cut into few centimetre pieces. This might have indicated that in the forming process something happened. Were larger stresses evoked? Or did the movements of the plies relative to each other in the forming, cause the deterioration of the bonding?

When studying the delamination of formed specimens more closely, the damage in the individual veneers could be observed (see Figure 41 below). Were these cracks generated during the latest drying, as the delamination did or already during the forming process? Another question is, were there cracks also within the sample FG? If yes, that would have explained the increased moisture absorption compared with the flat Grada, G. This is something that needs further investigation.

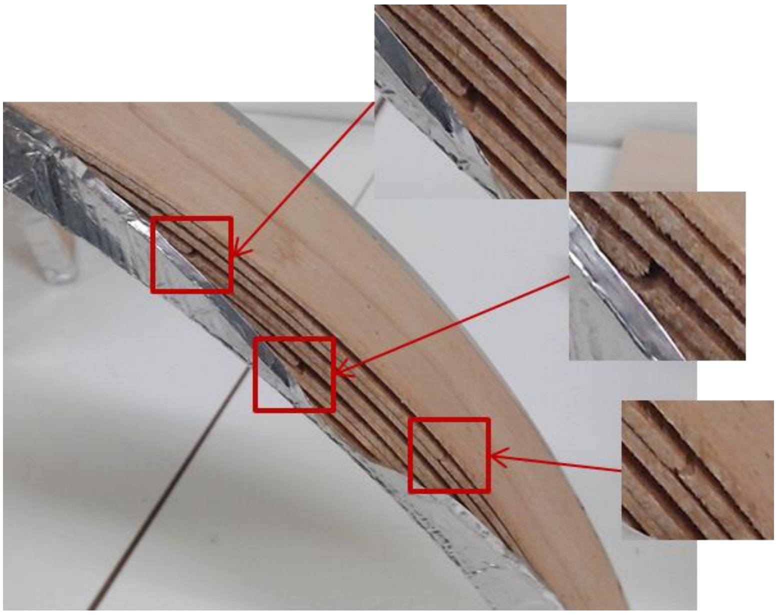

Figure 41 Damaged plies occurred after oven-drying - specimen UFG M 3

4.1.3 Moisture penetration and transportation through edges

4.1.3.1 Moisture transportation through all (four) edges

To study how the samples adsorb moisture through edges according to their side length and thickness ratio, the faces were sealed in three different sizes of specimens (50mm, 100mm and 150mm) in both samples: PW and G. The initial moisture content of G was somewhat more than two third of the MC of PW according to the moisture content pieces. Therefore the moisture content of G was expected to rise more than PW's. Due to the changes in the initial plan, the precise MC of the samples could not be determined. However, the estimation of the MC could be outlined with the assistance of the test in Section 3.2.1.4.

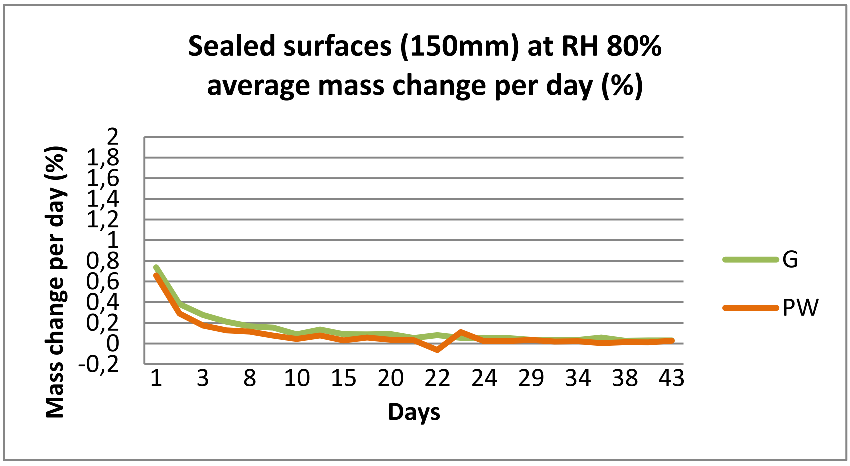

Figure 42 Sealed surfaces - Grada's and conventional plywood's average mass change per day in %

As can be observed from Figure 42 above, no strong differences could be seen between the materials, especially the kind that was found in the previous tests. In this test G absorbed moisture at a similar rate as PW and there were no such sharp peaks as could be seen in the previous tests, thus the reactivity of the Grada could not be observed when the edges were sealed.

When it comes into the effect of the side length/thickness ratio, the movements were the clearest for the specimen with the highest ratio and the ones having the smallest ratio had the mildest reactions, as predicted (see Figure 43).

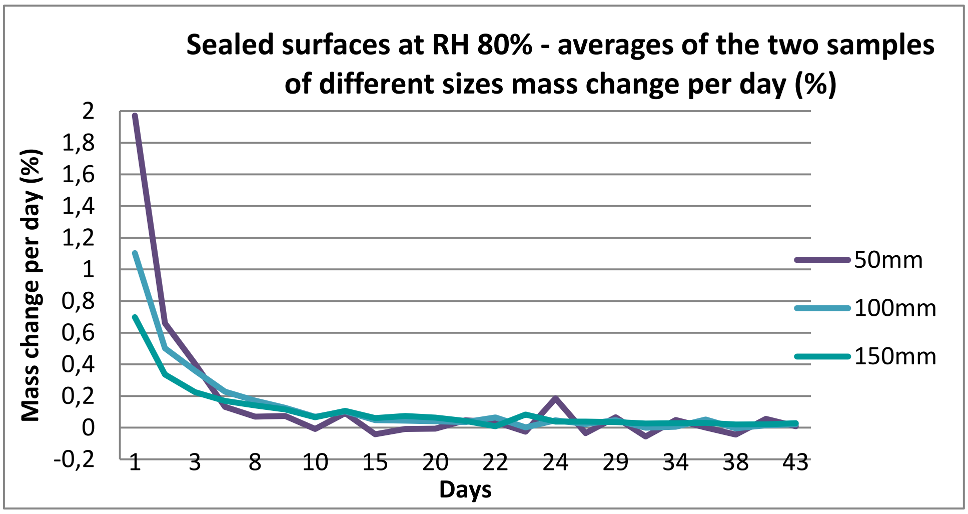

Figure 43 Sealed surfaces - the effect of the side length /thickness -ratio

The second part of this task was to study how the moisture was distributed within the specimen at the end of the exposed time. Within the smaller specimens, no difference between the materials appeared. However, after studying the largest specimen (side length 150mm) slight variance was noted (see Figure 44 below): MC in Grada was between 10.6% and 11.4% whereas in the conventional plywood it was 10.8-11.4%. As can be seen from the graphs, the predominant MC in G was 10.6-11.0%, whereas in PW it was clearly 11.0-11.4% – difference being 0.4 %.

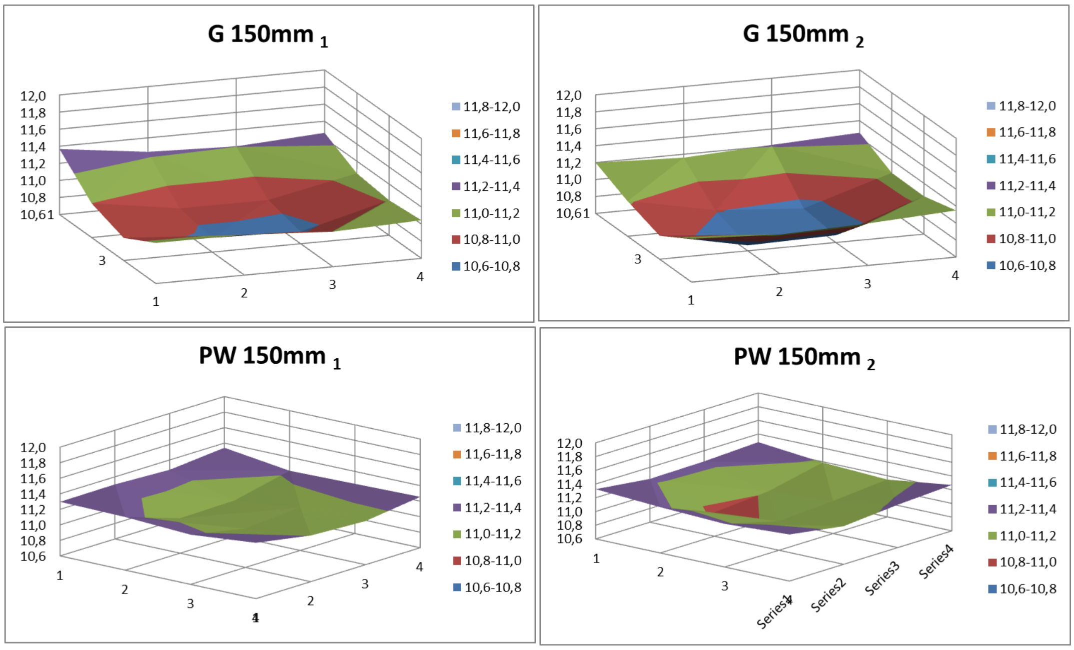

Figure 44 Moisture distribution within the 150mm samples after six weeks at RH80%

The MC in the centre parts in G was high though, around 10.7% compared with the initial MC (6%). In PW boards the percentage absorption was not as much due to the higher initial MC (8%). When it comes to the smaller samples the moisture content of G was even higher than PW's (see Figure 45 below).

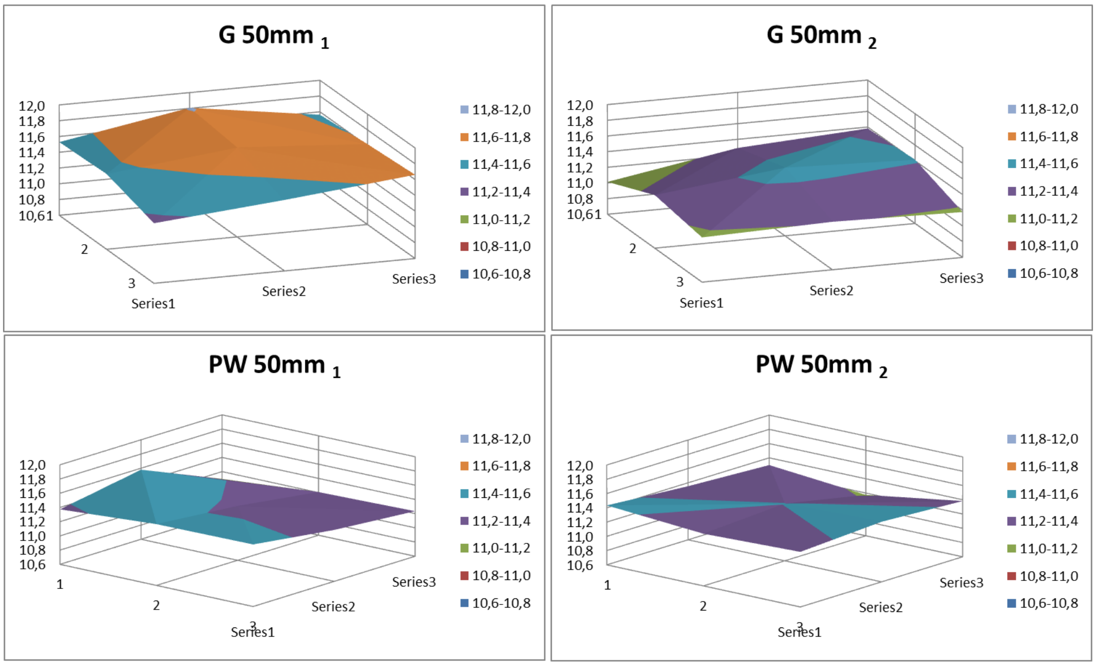

Figure 45 Moisture penetration within 50mm samples after six weeks at RH80%

The variance in the moisture distribution was slightly more apparent in G than in PW. It appeared that the MC in PW had already started to stabilize, since the MC in the middle of the specimens was equal to the edges.

There were only two (2) specimens per sample per length, thus no reliable conclusions could be withdrawn from this test. However, the aim was to gather some idea and hints of the behaviour, which was successful: no clear evidence about the effect of the bonding line in the edgewise direction could be found.

4.1.3.2 Moisture penetration and transportation through one edge

Moisture penetration in Grada and UF bonded birch plywood

From Figure 46 below, can be monitored a steadier moisture distribution of PW compared with Grada, where the moisture content difference between the first two measuring points (open edge and specimen 2) was almost twice as UF boards had. The latter did not even have such a difference through the whole specimen.

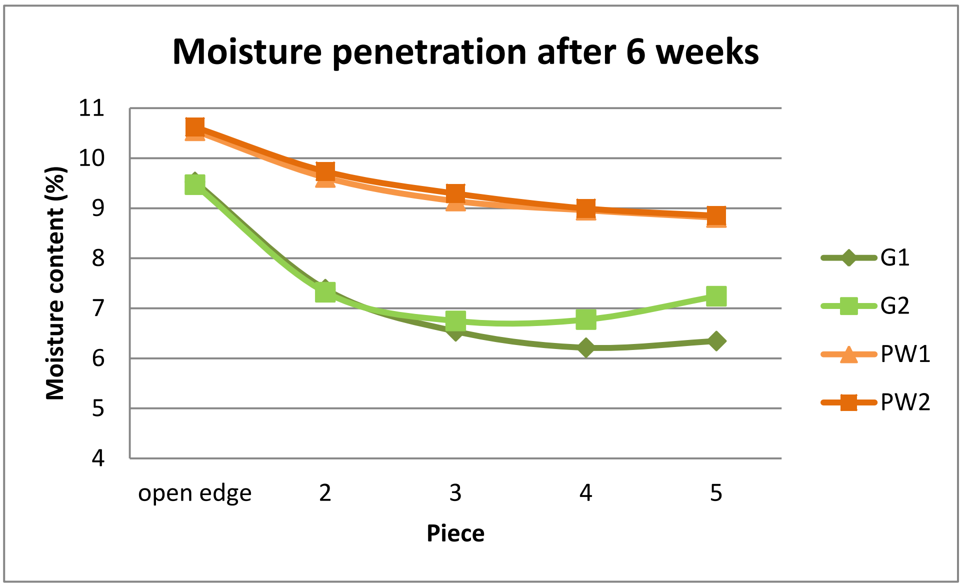

Figure 46 Moisture penetration in Grada and conventional plywood - only one edge open

The initial moisture content of the pieces was around 5.6% according to the task *Moisture penetration and transportation through the surfaces* (Section 4.1.2). The moisture content of G1's last two sections (pieces 4 and 5) at the end of the test was still around the initial moisture content of the sample, around 1% below it. However, no clear difference could be observed among the conventional plywood either, which initial MC was 7.8%. Proportionately, the polymer glued G specimen absorbed seemingly more moisture in the open edge (69.6%) than PW did (36.4%), the moisture seemed to be restrained to only the first part of the specimen though, as can be observed from the graph.

Results attained in section 4.1.2 had slight resemblance with the result of this task, even though the penetration direction was the opposite. The premier changes were distinctive, following with a steadier behaviour. Even though the specimens were several weeks (6) at the relative humidity of 80%, the moisture did not reach the end of the specimen.

A closer look at the graphs showed that in specimen G2 the curve rises towards the end. Two possible explanations could be provided. The initial MC distribution might have been uneven. As an example, if the specimen was located on the side of the larger plate, it might have absorbed humidity already before the being sawn. However, due to the later launching of the test, the sawn pieces could not be traced according to their position in the large plate and therefore no reliable conclusions could be drawn from this theory. Second alternative for the raise of the curve G2 might have been a discontinuity in the sealing. No visible cracking was seen however moisture penetration was not prevented if there were even microscopic holes. Specimen G1 did not show such a rise in the end – was it because of different location in the board before sawing or a smooth sealing line? Third option was as simple as a natural variance in the wood material.

Due to the deficiency of the material, the specimen used in the last stability task, were not identical concerning the direction of the plies. Both of the samples, G and PW, were manufactured from plywood of 11 plies, however they were sawn in different directions. That is to say – both had 10 plies in the same direction, but the 11th was in opposite direction: for PW board the 11th ply was in the longitudinal direction whereas for the formable the last ply was perpendicular to the grain direction. Obviously the moisture transport varies along the sorption direction and therefore this had had some influence on the results. One ply from 11 plies is 9%. As we can observe from the previous task, the sorption rate of veneers in the radial direction was 71% of the rate in longitudinal direction. We might presume that in overall the results twisted 29% on the 9% (i.e. the moisture absorption was 29% less in the 11th ply of Grada boards). Thus the moisture content of Grada was to be 2.6% lower than it would have been if all the veneers were in the same direction as in Grada. 2.6% from the highest moisture content of UF board (10.62%) is 0.28%. Thus the skewing of the results was not significant. If the 0.28% was added to the highest value of Grada (MC 9.52%), the updated value (9.80%) is still clearly below the lowest value of UF (10.55%). However the overall difference between these two samples was not as significant as in the former test, thus no clear evidence could be found about the effect of the thermoplastic bonding in the edgewise direction.

Moisture penetration in specimens with plies in the same direction, in special thermoplastic material

As predicted, the penetration was stronger in the longitudinal direction (green colour), especially during the first week. After that the mass changes were practically the same in both directions, no clear divergence in the changes appeared (see Figure 47 below). This was predicted due to the peculiar behaviour of wood material absorbing moisture differently in different directions.

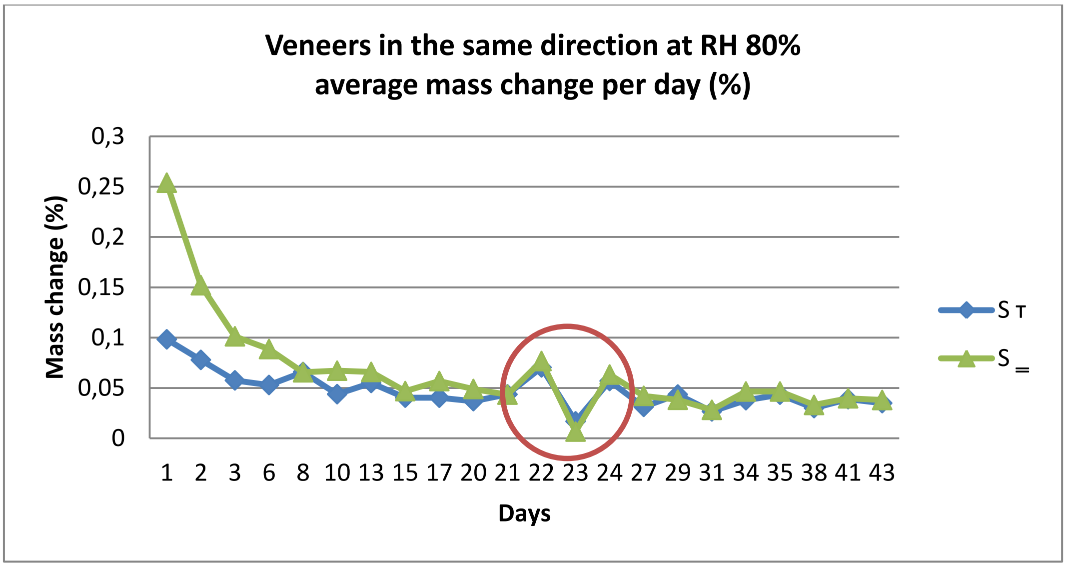

Figure 47 Average of the percentage mass change in plates with veneer is the same direction (special made product)

The specimens were sawn into smaller pieces after being the exposed in the cabin, to see the moisture distribution inside the specimens and hence the reason behind the slowdown of the mass changes. This will be discussed at the end of this section.

When observing Figure 47 more closely, a clear irregularity could be found on the percentage difference on the 22nd day of the experiment (the 24th of August). Similar sudden changes in mass occurred in other specimens in Cabin two, which indicates that there had been a failure in the function of the Cabin two, as mentioned in the very beginning of the chapter.

After oven-drying the pieces moisture maps were drawn (see Figure 48 below).

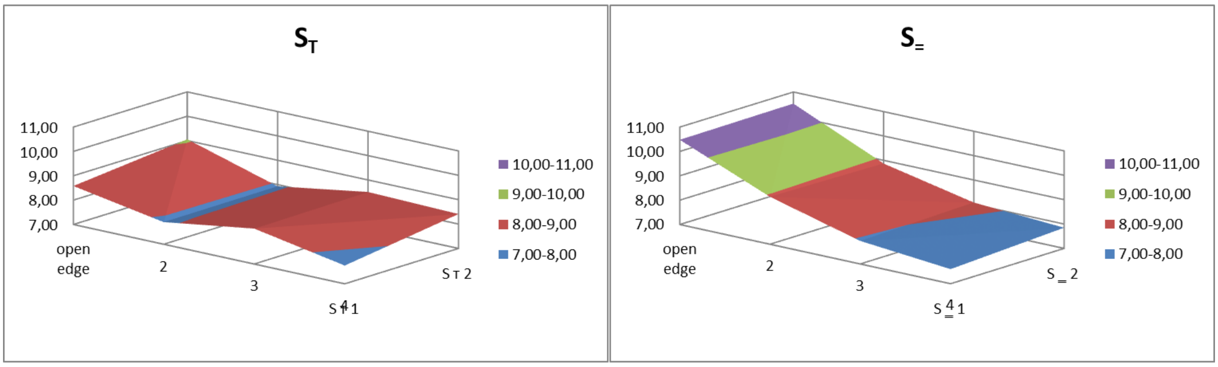

Figure 48 Moisture distribution in plywood with veneers in the same direction. On the left hand the penetration direction is perpendicular to the grain direction, on the right hand penetration is along the grain direction (two specimens per sample).

The moisture penetrated faster in the longitudinal direction (on the right), which can be observed from the graphs above (Figure 48). Interesting observation in sample S_T (on the left) was the decrease in the moisture content in Section two, after the open end, as well as the higher MC at the end of the other specimen (S_T3). These anomalies might, however, have been derived from uneven MC in the very beginning, which unfortunately could not be studied afterwards.

In sample $S_=$ (on the right) the moisture absorption was higher in the first two segments. In the last segment, the MC was still below 8%. Thus, even with the intensified circumstances (all veneers in the longitudinal direction, six weeks at RH80%) the moisture content remains below 8%. As there was no proper comparable product it could not be stated that the influence was due to the bonding and not the lower moisture content of the veneers though.

4.1.4 Conclusion of the stability of the product

Grada seemed genuinely an interesting product: being reactive to the environment and meantime more stable in a long term. It is undeniable that the thermoplastic bonded flat Grada was distinctively more resistant to the moisture absorption than the conventional product. At the beginning of the exposure, the product reacted faster to the changes in the surrounding conditions throughout several tests (e.g. flatness and moisture penetration). The reactivity is assumed to derive from the clearly lower moisture content of the surface veneers. After penetrating the surface veneers, the absorption as well the dimensional changes seemed to be bared or at least clearly hindered, which could be seen from the sharp peaks, among all the thermoplastic products, G, FG and UFG. *To be noted that there was no clear evidence of the validity of these properties in the edgewise direction.*

Even though formed Gradas were expected to be even more resistant to the moisture absorption than the flat thermoplastic, due to the re-heating while forming, it was the opposite. When studying the percentage moisture changes the flat Grada proved to be the most resistant: the percentage change from RH50% to RH 80% was below 25%, whereas for FG it was 56%. The unsanded proved to be in its own category with 76%. The clearly higher values of UFG can be assumed to derive from the thicker surface veneers, i.e. there was more material into which the moisture could absorb to, thus its behaviour simulated the behaviour of wood. Further on, the difference between the formed and flat thermoplastics was the most likely due to the inner stresses, which in some cases have evoked cracks on the material, especially among the unsanded one. These cracks enabled further penetration into the inner parts of the specimen. As referred in the literature review, the cracks have a great influence on the diffusivity of plywood [Absetz 1999]. It remained unsolved whether there were cracks also among the FGs or were the cracks of the UFG developed during the delamination. The percentage moisture content changes refer that there would have been at least some cracks.

When it comes to the delamination itself within the sample UFG, it appeared foremost on the side of the U-formed specimen (see Appendix). From this it can be concluded that it was the high pressure (due to the greater thickness) and inner stresses combined with higher moisture content that may have evoked the delamination.

The diameter change was clearly more dramatic among the thermoplastics, FG and UFG, than for the formed beech. However, the moisture absorption of beech was not clearly inferior: when augmenting the relative humidity up to 80% the percentage change was around 51%, vs. FG's 56%, which did not explain the tremendous difference in the diameter change. Was there something else then? Beech had been delivered from Italy and the time of manufacturing was indeterminate. The external minor damages and marks referred that the sample had been fabricated already a while ago, thus there is a possibility that the beech sample had had time to adjust to the surrounding conditions, especially since it was delivered from more humid conditions, Italy. On the contrary, the thermoplastic had just been fabricated right before the experiments. Nonetheless, beech is common material used in rotary dies and therefore it was an approved as a comparable product.

4.2 Strength properties of the product

There are numerous ways to define strength properties of a plywood: bending, hardness, tension, compression, impact, and shear resistance. In this research, our focus was on the bending tests, which results are shown first. Also compression, tension and impact strengths were utilised, but in an adjusted way.

4.2.1 Three-point bending

Samples were in conditioning room from the 29th of April. However, within one or two weeks, the surface veneer of one Grada test specimen had delaminated and made a curve of approximately 20mm. Due to the deformation on the specimen, a new test batch was chosen. This new batch of G was in the conditioning from the 20th of May. After the G had been in conditioning for nearly four months, the moisture content was approximately 9.2%. The conventional plywood, which had been three weeks' longer period in conditioning, its MC was somewhat higher (ca. 9.9%). This difference could be presumed to be minimal to have an effect on the results.

The actual three-point bending test supported the thought of Grada as a composite-like product. No difference between the longitudinal or transverse specimens could be seen in the modulus of rupture (MOR).

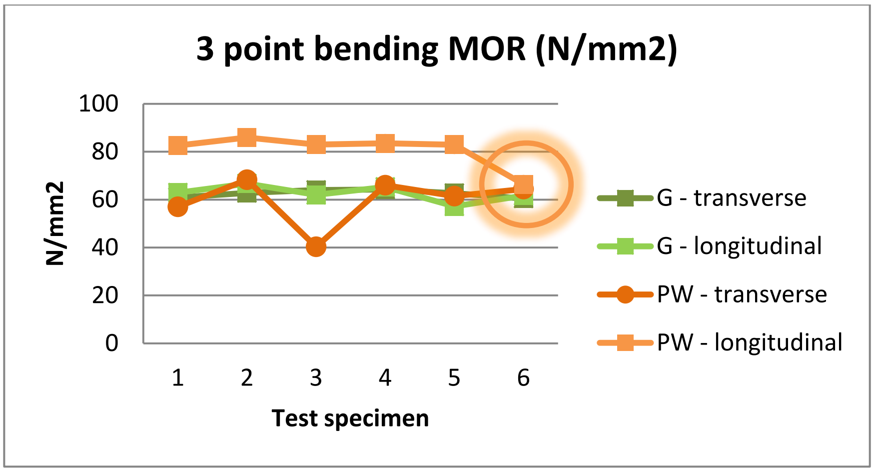

Figure 49 Three-point bending MOR

The average MOR for Grada in the longitudinal direction was 62.63N/mm^2 and in transverse 62.51N/mm^2. For the conventional plywood, difference was substantially larger: 80.72 N/mm^2 and 59.60 N/mm^2 with standard deviation of 13.86, whereas for Grada it was 2.46. The difference between the materials was also seen when calculating a standard deviation, **σ** (see Table 6 below).

Table 6 Modulus of rupture and elasticity in transverse and longitudinal directions

MOR (n)	Grada	PW
av. transverse (6)	62.52	59.60
av. longitudinal (6)	62.63	80.72
σ transverse	1.54	10.23
σ longitudinal	3.30	7.11
Av. total (12)	62.58	70.16
σ total	2.46	13.86

MOE (n)	Grada	PW
av. transverse (6)	6.69	5.68
av. longitudinal (6)	7.91	9.18
σ transverse	0.36	0.43
σ longitudinal	0.29	0.38
Av. total (12)	7.30	7.43
σ total	0.71	1.87

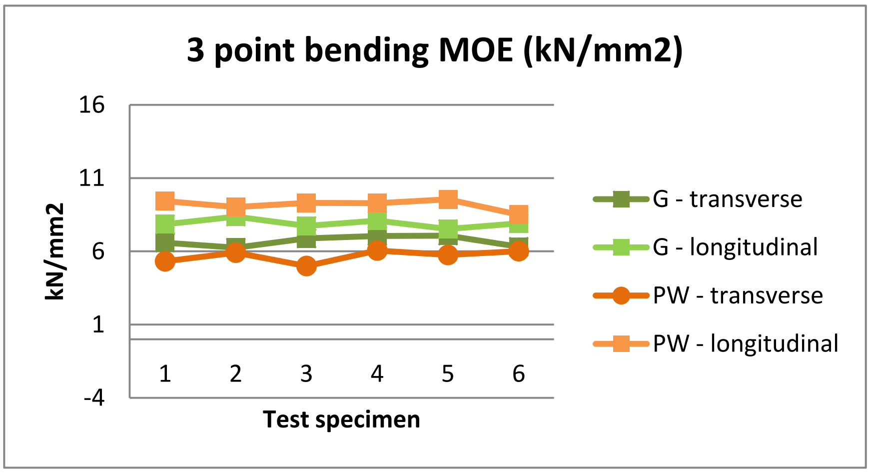

Figure 50 Three-point bending MOE

In the Modulus of elasticity, the distinction between the materials remained, even though light variance between the bending directions started to occur for Grada as well. This indicates that the adhesive used in Grada, unified the amount of force the material is able to tolerate. In elasticity, the impact of the bending direction was more distinctive.

From Figure 49 can be seen that the specimen PW 6 in the longitudinal direction attained the lowest strength values of the sample. The above-mentioned specimen attained only 66.4N/mm2 whereas the other specimens within the longitudinal PW sample attained at least 82.6N/mm2, thus there was an apparent distinction. When studying the specimen PW6 more closely, it was observed that there was a patch precisely on the cracking position (see Figure 51 below). The patch may have affected the results, being the only weak transverse specimen.

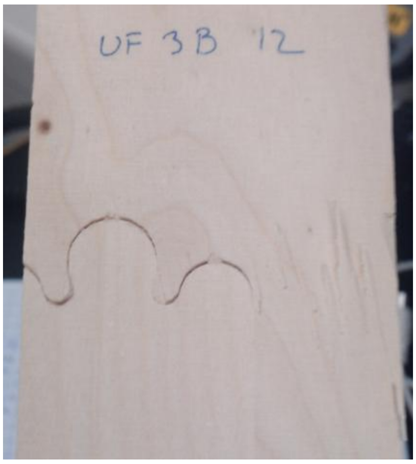

Figure 51 Three-point bending test - patch on the test specimen PW $6_{longitudinal}$

If the specimen PW $6_{longitudinal}$ was left aside, the inner variance within the longitudinal PW would have clearly be reduced. In the meantime, it would have naturally widened the difference between the materials' total variances (see Table 7 Revised MOR and MOE values below).

Table 7 Revised MOR and MOE values

MOR (n)	Grada	PW
av. transverse (6)	62.52	59.60
av. longitudinal (6,5)	62.63	83.58
σ transverse	1.54	10.23
σ longitudinal	3.30	1.34
av total (12, 11)	62.58	70.50
σ total	2.46	14.49

MOE (n)	Grada	PW
av. transverse (6)	6.69	5.68
av. longitudinal (6,5)	7.91	9.32
σ transverse	0.36	0.43
σ longitudinal	0.29	0.19
av total (12,11)	7.30	7.43
σ total	0.71	1.93

When studying the Figure 49 further on, another inconsistent value was found: specimen PW $3_{transverse}$, which diverged clearly from the other transverse bending specimens. This leads to the following question: did the scattered values result from the characteristic behaviour of wood? As observed from the previous results, Grada seemed to reduce the traditional heterogeneous characteristics of wood.

4.2.2 Four-point bending

As in the three point bending test, in the four-point bending test the MC difference was also minimal between the samples (9.0% vs. 9.9%), thus the values were not adjusted in this test either.

In the four-point bending Grada showed still somewhat more uniform behaviour than the conventional plywood (see Figure 52), however the difference between these two materials was not as wide as in the three point bending. In the transverse direction the values had dropped down to 40N/mm^3 for four Grada specimens.

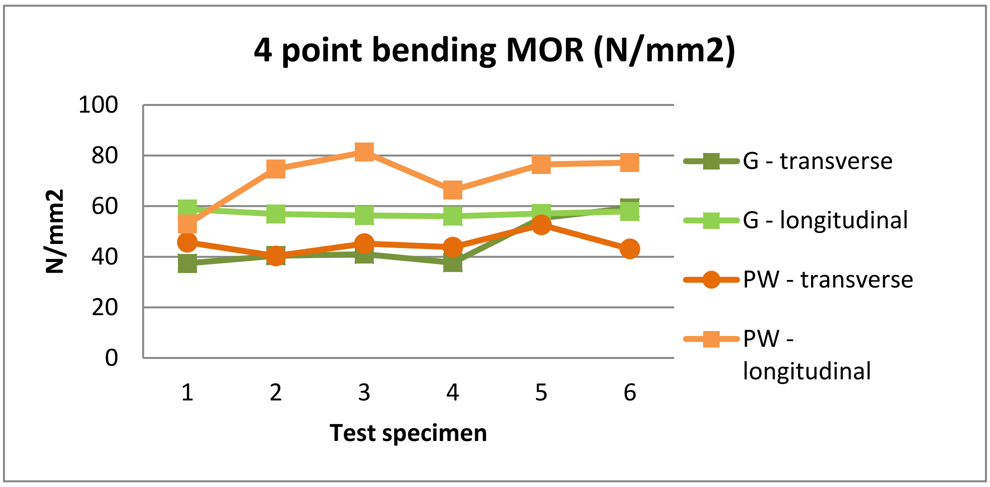

Figure 52 Four-point bending MOR

Where did this change of behaviour derive from? In the four-point bending, the stress is spread on a wider range, i.e. between the supports, whereas in three-point bending the stress is more pointed. Nevertheless, when studying the bending graphs, the material difference can clearly be seen in the longitudinal direction.

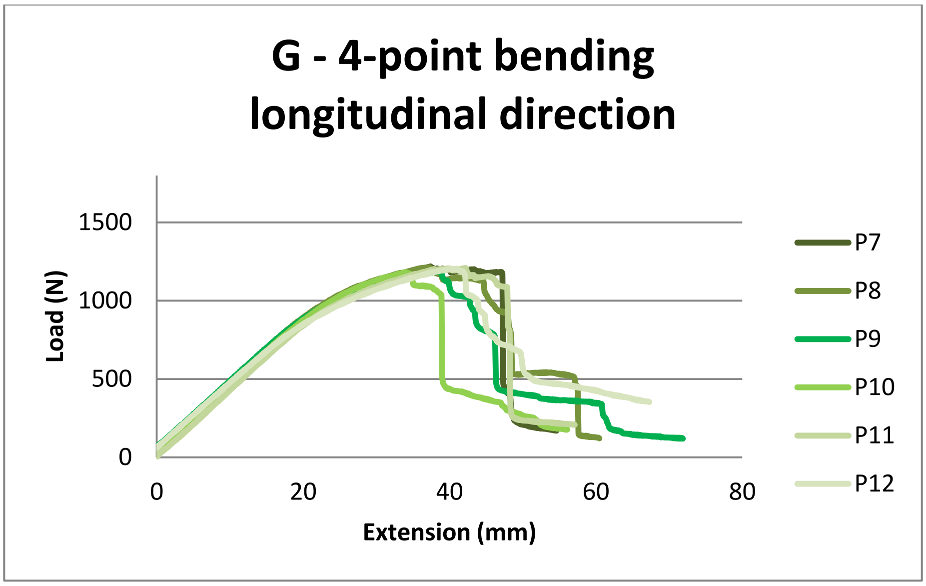

Figure 53 Grada - four-point bending, longitudinal direction

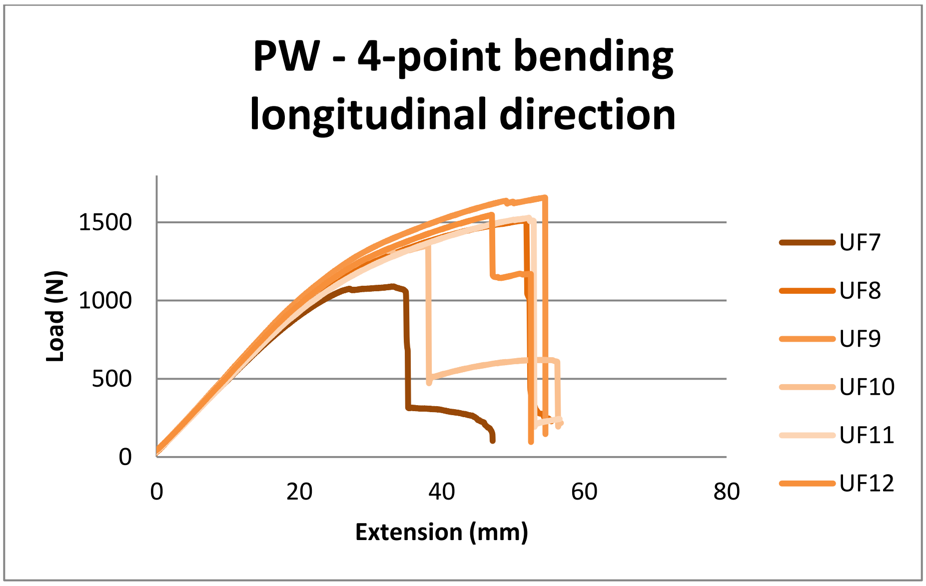

Figure 54 PW - four-point bending, longitudinal direction

After Grada attained the maximum values in loading, a clear “flexibility” appeared, as the Figure 53 Figure 54 show. The load-extension curve decreased gradually for Grada and the material did not yield right after attaining the maximum load, which was characteristic for PW. Another interesting thing appeared: the maximum force for Grada in the longitudinal direction was almost identical for all six specimens, the standard deviation being below 15. For conventional plywood σ was above 200.

However, in the transverse direction the differences between the materials seemed to dwindle or even go to the opposite direction. The dispersion of maximum forces in transverse direction for Grada was high: 192 vs. 83 for PW (see Figure 55 below and Figure 52 above).

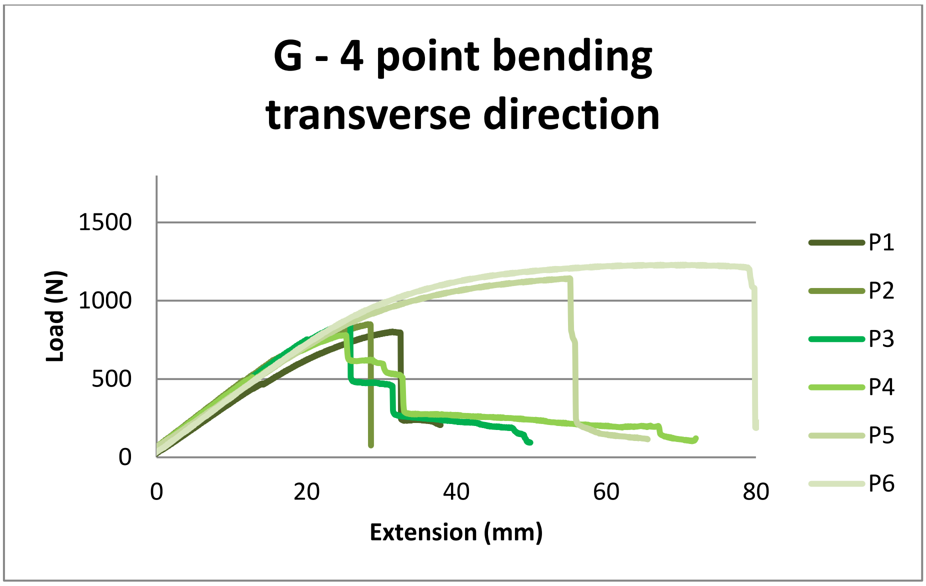

Figure 55 G - four-point bending, trasverse direction

In addition, the behaviour after attaining the maximum force resembled more like the conventional plywood, being sharper. Only two specimens (P3 and P4) out of six resembled the earlier "flexible" behaviour of Grada.

Table 8 Modulus of rupture and elasticity in transverse and longitudinal directions

MOR (n)	Grada	PW
av. transverse (6)	45.18	45.12
av. longitudinal (6)	57.17	71.48
σ transverse	9.58	4.13
σ longitudinal	1.04	10.36
av total (12)	51.18	58.30
σ total	9.02	15.69

MOE (n)	Grada	PW
av. transverse (6)	10.21	8.88
av. longitudinal (6)	12.55	13.23
σ transverse	0.72	0.28
σ longitudinal	1.17	0.45
av total (12)	11.38	11.06
σ total	1.53	2.30

There was an interesting detail on the dispersion values. Even though the MOR and maximum forces were less deviating for Grada in longitudinal direction, the deviation for MOE was superior to the one of PW (see Table 8). The difference was not tremendous though. However, the behaviour of Grada was clearly different than in the three-point bending test. Was this due to larger test specimens and longer supporting span? The span in three-point bending was 300mm, whereas in four-point bending test it was 598mm, thus the exposed area was twice as large and the probability of a defect is higher. Were the properties of the wood material pronounced as the exposed area widened? Or did the bending in four-point evoke deterioration of the adhesion, leading into microscopic delamination and weakening of the covalent bonding?

4.2.3 Compression and tension of the "U"-formed board

This test was conducted with minimal amount of test specimen, thus no reliable results could be drawn from these tests. Some hints about the behaviour could be seen though, which was the intention of these tests.

The moisture contents of the thermoplastic bonded Gradas were parallel: UFG 8.9% and FG 9%. The beech appeared to be still a bit moister: 10.8%. This may had a small influence on the results, since wood strength properties are better in lower moisture contents.

Compression

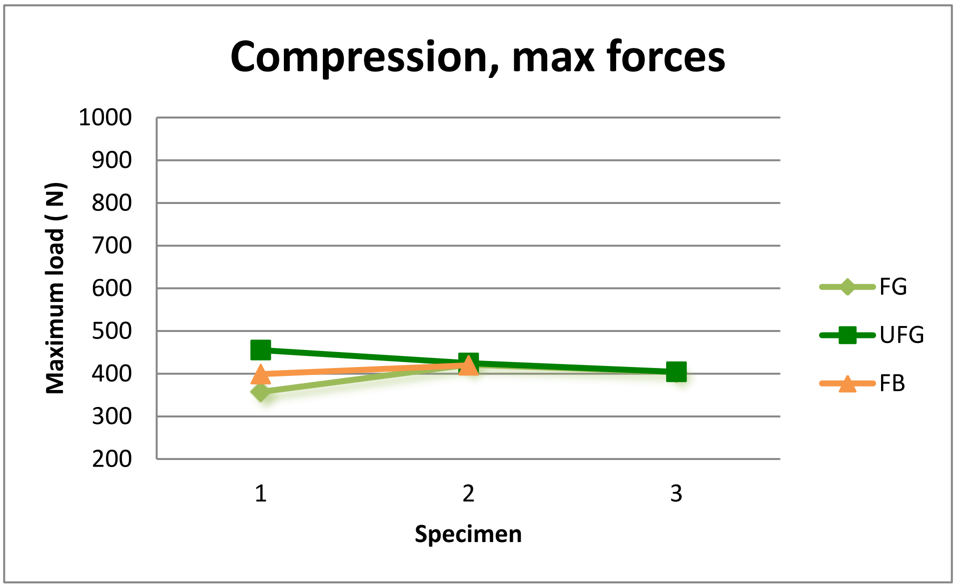

Figure 56 Compression test for the formed specimens

As can be seen from the Figure 56, all the three materials seemed to attain approximately the same maximum load values, around 400N each. UFG attained the highest value for the first specimen, which increased batch's average. For the FG the values appeared to scatter slightly more than in the bending tests. Was this due to fewer test specimens, or did it result from the material itself – did the effect of the adhesive, i.e. the bonding decline under compression?

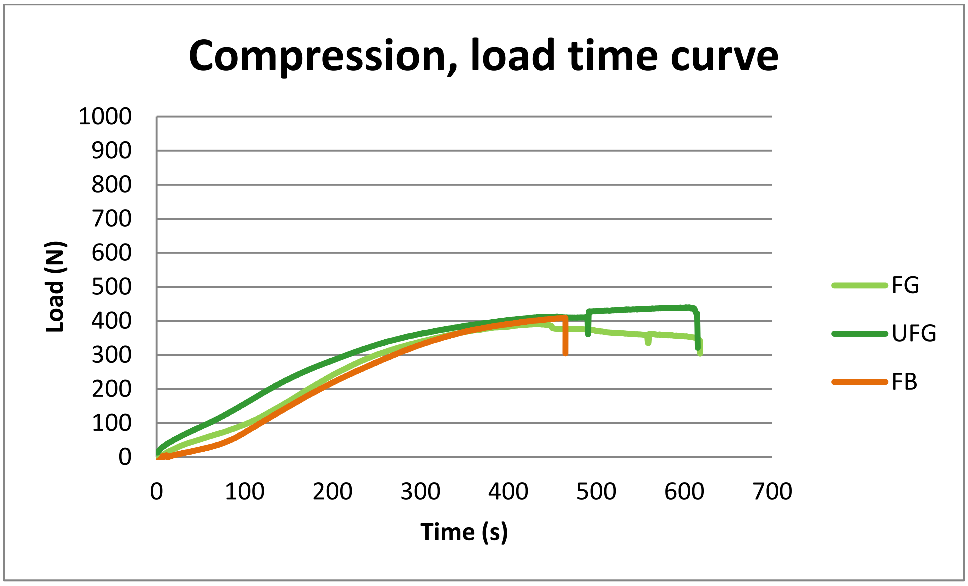

Figure 57 The load-time curve for the compression samples: FG, UFG and FB

When studying the load-time curves (see Figure 57) FG seemed to follow similar behaviour as observed in previous strength tests: the breakage was “flexible” and was not sudden which was more peculiar for FB. In that manner, the behaviour of UFG lay between the FG and FB. The only known difference between FG and UFG was the relative amount of wood, due to the sanding of FG before forming process. This leads to an assumption that the factor inducing the uniformity was partly due to the lower percentage of wood on the plywood surface.

In tension test similar behaviour could be found.

Tension

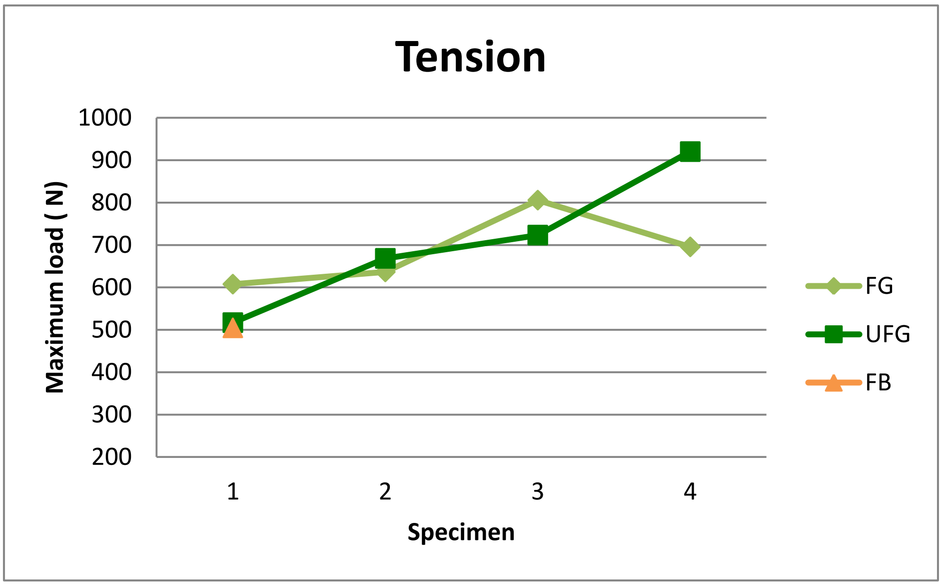

Figure 58 Tension test for formed specimens

In the tension test of the formed samples, the values attained were clearly higher than the ones of the compression test, as can be observed from the Figure 58.

Despite the higher magnitude of the maximum loads, similar differences in the behaviour of the three materials appeared also in tension test. For the actual Grada, FG, the attained values were all between 600N and 800N, whereas for the unsanded one, UFG, the values scattered approximately from 540N to 920N. The sole formed beech specimen attained rather low value, being below both Gradas. In this test also the load-time curve showed characteristic behaviour of Grada, being flexible, yielding gradually.

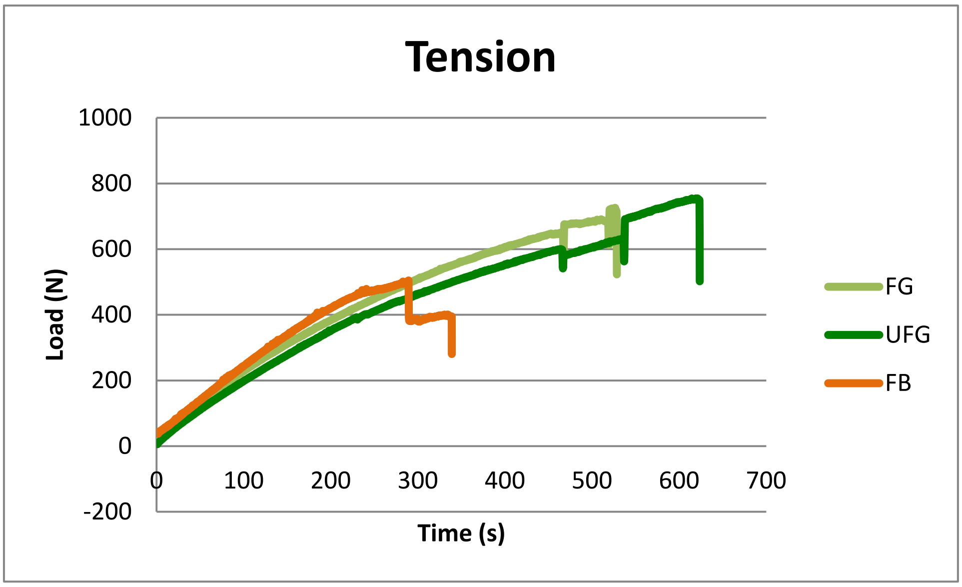

Figure 59 The load-time curve for the tension samples: FG, UFG and FB

4.2.4 Charpy Impact test (high strain rate)

No strong divergence was presumed to arise in the impact test. Nevertheless, the results of the test were proved to be the opposite, in diverse ways.

Table 9 Impact test for FG, G and PW

	Formed Grada Edgewise	Formed Grada Flatwise	Formable Grada Edgewise	Formable Grada Flatwise	Flat PW Edgewise	Flat PW Flatwise
Impact energy (J/m^2)	82	99	63	720	301	362
STDEV (%)	55	35	5	13	94	55
Max value	169	190	66	843	800	637
Min value	52	63	57	547	73	127

The thickness of the PW and Grada plates was unequal (the thickness of FG was 12.75mm < PW, 14.75mm < G, 15.00mm), however, the thickness of G and PW were enough close to each other's to attain valid comparisons. Within the conventional plywood, the averages attained in flat and edgewise were close to each other, and remained around 330J/m2 (see Table 9), whereas for Grada the differences between the breaking directions were distinctive: 63J/m2 in the edgewise direction and 720J/m2 in flatwise. This is rather interesting since in bending tests the difference between directions was tangential. However, even though the contrast between the directions is explicit, the standard deviation within each direction is clearly lower than for the PW: percentage standard deviation for Grada 5% in flatwise direction and 13% in edgewise direction. For PW, the deviation was almost 10 times higher: 55% in flatwise and even 94% in the edgewise direction.

The deviation differences between the materials strengthened the perception of the composite like the behaviour of Grada. In literature review it was stated that the impact strength was sensitive to even minuscule deformations, which can be observed from the values PW attained. However, what was the role of the thermoplastic bonding? Were the plies of better quality, with fewer defects, or did the bonding really dim the effect of the defects? According to UPM, the plies were identical in both materials, which would lead to a conclusion that the thermoplastic absorbs the impact or obscures the defects on wood material.

4.2.5 Conclusion of the strength properties of the product

The uniform behaviour that occurred in the stability section was present also in the strength properties –section, even more distinctively. Among all the tests, Grada proved to be clearly more uniform than conventional UF-bonded plywood, in the three point bending test even the bending directions appeared to be uniform. In the impact test in which the specimens' defects were accentuated, Grada still attained peculiarly consistent values. The thermoplastic bonding indicated a clear fading of the defects in the heterogeneous wood material, bringing it more homogenous. It may be presumed due to the covalent bonding between the adhesive and the plies, which enhances the bonding. Another option is that the thermoplastic bonding was eventually weaker. As Obersriebnig et al. [2013] stated, the better the adhesion is, the stronger is the failure in wood. When visually studying the bending specimens, the stronger wood failures were characteristic for the UF bonded plywood. Whereas, the failures in wood were more difficult to observe among Grada specimens. The homogenous bond-line of Grada would explain the consistency of the results on the strength tests.

The sole exception for the uniformity of Grada was the 4-point bending in the transverse direction, in which the standard deviation was twice as much for the UF-bonded plywood. This variation indicated that the wider exposure area for the bending stress deteriorates the effect of the thermoplastic bonding. Was it due to the higher probability of the defects? Or did the specimens start to delaminate?

Even though the values within the static tests were more uniform among Grada specimens, the strength values were not as high as for the conventional material. The bending tests often study the bonding. Grada could not absorb stress as much as the conventional plywood; was it due to inferior ability to transfer the stress into the wood? Or was it simply because of less vigorous bonding? Or had the bond of Grada been inadequately formed?

5 CONCLUSIONS AND RECOMMENDATIONS

Environmental aspect is gaining more and more space. People are seeking products with lower carbon footprints and companies are aiming to be in the frontline with high environmental values. Wooden composites are raising interest and in some countries the percentage of use of wooden building materials has been defined through legislation. Wood has its pros and cons, but this environmental interest has put further pressure to deduct the disadvantages, which are mainly due to the tendency to absorb surrounding moisture, which affects several other wood properties. Furthermore, the fabrication of wood products has been reviewed as well; there is a common will to avoid the hazardous formaldehyde in gluing. In Grada it appears that several of the unwanted properties would have been eliminated. First of all, the adhesive is formaldehyde-free and in a solid phase. In addition there is a clear indication of the material to be more resistant to surrounding condition changes, especially among the flat Grada. The formed Grada also performed well, being slightly less resistant though. The bond-line proved to distinctively hinder the moisture absorption, as the diffusion rate diminished radically after the beginning. However, the absorption was not entirely inhibited, which could be seen especially among the formed Grada (FG) specimens, in which the surface veneers were thinner due to the sanding. At the beginning, it was assumed that due to the re-heating, the formed Grada (FG) might have superior moisture resistance than the flat one. Nevertheless, it was proved to be the opposite. This indicates that during the forming, microscopic cracks had occurred, increasing the diffusion rate.

Unsanded formed Grada (UFG) emerged to behave more like conventional plywood, the performance peculiar to wood differentiated it from the sanded formed Grada. Certainly the thicker surface veneers were presumably the most evident reason for this behaviour. However, the relative wood content did not seem high enough to solely explain the phenomenon. Other reasons behind the behaviour appeared to be the microscopic cracks in the plywood, caused by inner tensions, derived from the forming process. The form used in the process had been designed for slightly thinner plates, which might have evoked further inner stress. As stated in the literature review, the inner tensions tend to increase the EMC [Absetz 1999], which can be assumed to be also behind this behaviour. The cracks, which were observed after drying the specimens, indicated that some stresses were evoked during the forming and presumably had affected the penetration rate as well.

The moisture absorption of the formed Grada (FG) was connected to the one of the comparable product, UF-bonded beech, with a few percentages’ difference. Nonetheless the dimensional stability was inferior to the comparable product, which is today the most used material in rotary dies. No reliable conclusions could be drawn from this difference though, since the beech sample had been manufactured earlier and delivered from Italy, i.e. from clearly moister conditions. What could be concluded though, was the relation of moisture absorption and dimensional changes, which was stronger for Grada. Still, would it have been if their initial moisture contents were the same? That remains unsolved within this research.

The stability of the flat Grada appeared to be more reactive than the conventional plywood. However, in a long-term it proved to be more stable. The changes were observed through minute changes as the gauge was laid on the specimen. In further investigation it would be recommended though to also study the flatness without laying the gauge on the specimens, to attain the overall changes in dimensions, e.g. twisting.

One of the objectives of this research was to learn about the flexibility of Grada. This feature was discovered through the bending tests where Grada proved to bend gradually, being flexible. The conventional plywood tent to yield right after attaining the maximum load, whereas Grada appeared to bear the load and yielding progressively, being more flexible. The strength test proved Grada to be an interesting wood composite, being clearly more uniform and attained more consistent values. With the exception of a part of one test, Grada attained test after test exceptionally low deviations, distinguishing from the conventional plywood. From this behaviour could be concluded that the thermoplastic bonding by some means deduces the effect of the heterogeneous wood and meantime brings the material more elastic. Even though the values were clearly more uniform, it appeared that Grada could not absorb as much load as did the conventional plywood. Was the thermoplastic bonding able to transfer the stress to the plies as it does in conventional plywood? Did the loading strain only the glue-line?

The impact test and moisture penetration tests investigated the performance of the thermoplastic also in edgewise, however no clear evidence of the effect could be derived. Even though it can be presumed to create covalent bonding with the plies, the influence further into the veneers could not be proved.

It would have been interesting to compare the moisture behaviour of Grada with the phenol-formaldehyde (PF) adhesive, which is used in exterior applications due to its better moisture resistance compared with the urea formaldehyde bonded plywood, which is solely used in interior applications due to its poor moisture resistance [Dunky 1998]. However, since the PF-bonded plywood cannot be used in laser cutting, it would not have served the purpose of the research, since one of Grada's end uses is in laser cutting. Apart from the PF adhesive, it would have been interesting to compare the behaviour with coated plywood as well. This might have brought some relevant outcomes in the economical point of view.

Other recommendations for further research would be to conduct the stability tests with specimens of equal initial moisture content. Since wood behaves differently in distinctive moisture contents, if the time permits, it would be advantageous to carry out the tests with samples of similar moisture contents, to ensure that the findings are valid then as well.

The information gathered within this research was intriguing and led to a better understanding of the behaviour of the new innovative plywood product, Grada. Grada was found to be a novel wood product between the conventional plywood and the wood plastic composite. Compared with the first mentioned, in several occasions Grada proved to be more uniform and to behave more systematically, which is not peculiar to the traditional wood products. With the appearance of plywood and with the properties of a composite, the possibilities that this product introduces are compelling!

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7 APPENDICES

APPENDIX I (1/2) - STABILITY OF THE FORMED PRODUCT, *DIAMETER CHANGE*

	Specimen	FG S 1 Diameter change (mm)			FG S 2 Diameter change (mm)			FG S 3 Diameter change (mm)			FG S 4 Diameter change (mm)		
28.6.	number of days in the conditions	1	2	3	1	2	3	1	2	3	1	2	3
30.6.	RH 50% 2	0.13	0.23	0.40	0.45	-0.01	0.05	0.19	0.16	0.09	0.29	0.70	-0.68
2.7.	4	0.25	0.32	0.57	0.58	0.26	0.27	0.15	0.37	0.08	0.28	0.22	0.16
4.7.	6	0.38	0.44	0.70	0.83	0.36	0.54	0.48	0.46	0.27	0.58	0.41	0.38
6.7.	8	0.59	0.66	0.83	0.83	0.71	0.81	0.60	0.55	0.49	0.61	0.54	0.47
8.7.	10	0.70	0.92	1.07	1.14	0.82	1.00	0.77	0.72	0.63	0.91	0.72	0.77
11.7.	13	0.81	0.96	1.24	1.22	1.08	1.12	0.85	0.87	0.81	1.05	0.90	0.77
13.7.	RH 80% 1	2.52	2.58	3.29	3.12	2.47	2.47	2.63	2.62	2.55	2.38	2.24	2.34
14.7.	2	2.86	2.93	3.65	3.44	2.73	2.87	2.88	2.88	2.83	2.67	2.43	2.61
15.7.	3	3.21	3.44	4.02	3.75	3.03	3.18	3.24	3.27	3.16	3.04	2.78	3.11
18.7.	6	4.17	4.27	4.85	4.64	3.92	4.31	4.04	4.11	4.16	3.71	3.45	3.72
20.7.	8	4.47	4.75	5.64	5.31	4.52	4.86	4.43	4.48	4.70	4.13	3.88	4.09
22.7.	10	4.69	4.94	6.03	5.61	4.82	5.03	4.87	4.98	4.99	4.33	4.18	4.49
25.7.	13	5.41	5.59	6.58	6.27	5.42	5.61	5.40	5.42	5.52	4.85	4.73	4.90
27.7.	15	5.71	5.94	6.86	6.53	5.77	6.00	5.75	5.75	5.83	5.05	5.03	5.17
29.7.	17	6.00	6.27	7.25	6.86	6.14	6.32	6.16	6.17	6.17	5.36	5.31	5.63
1.8.	20	6.52	6.75	7.63	7.35	6.61	6.77	6.38	6.50	6.51	6.03	5.81	6.04
3.8.	RH 30% 1	5.17	5.51	5.94	6.11	5.76	6.05	4.97	5.11	4.75	5.03	4.83	4.58
4.8.	2	5.00	5.29	5.68	6.01	5.84	5.98	4.87	4.95	4.62	4.99	4.87	4.56
5.8.	3	4.81	5.20	5.52	5.91	5.63	5.78	4.65	4.81	4.41	4.85	4.73	4.30
8.8.	6	4.54	5.02	5.08	5.44	5.31	5.39	4.35	4.55	3.97	4.61	4.39	4.09
10.8.	8	4.38	4.82	4.89	5.29	5.03	5.13	4.21	4.33	3.81	4.49	4.42	3.99
12.8.	10	4.25	4.71	4.79	4.76	4.86	4.91	4.16	4.30	3.68	4.43	4.24	3.81
15.8.	13	3.97	4.47	4.47	4.79	4.62	4.59	3.96	3.99	3.55	4.37	4.17	3.75
17.8.	15	3.99	4.37	4.48	4.80	4.62	4.57	3.84	3.92	3.36	4.14	4.01	3.64
19.8.	17	3.73	4.21	4.30	4.65	4.47	4.44	3.84	3.89	3.31	4.21	4.02	3.48
22.8.	20	3.72	4.11	4.20	4.61	4.42	4.29	3.82	3.77	3.29	4.12	3.92	3.49
23.8.	RH 50% 0	3.90	4.37	4.30	4.92	4.65	4.58	3.99	4.00	3.57	4.19	4.02	3.66
24.8.	1	4.39	4.61	4.82	5.01	4.66	4.63	4.27	4.19	3.82	4.46	4.25	3.94
25.8.	2	4.28	4.67	4.94	5.16	4.83	4.76	4.34	4.33	4.03	4.71	4.29	4.06
26.8.	3	4.20	4.66	4.92	5.19	4.69	4.76	4.34	4.35	4.01	4.53	4.45	4.20
29.8.	6	4.39	4.73	5.10	5.35	4.98	5.09	4.49	4.51	4.17	4.69	4.48	4.21
31.8.	8	4.50	4.85	5.19	5.44	5.07	5.18	4.64	4.62	4.28	4.73	4.59	4.38
2.9.	10	4.65	5.03	5.31	5.55	5.02	5.23	4.67	4.68	4.34	4.74	4.57	4.36
5.9.	13	4.63	5.04	5.31	5.60	5.18	5.33	4.81	4.79	4.38	4.91	4.61	4.47
6.9.	14	4.69	5.09	5.44	5.72	5.39	5.47	4.82	4.79	4.52	4.96	4.75	4.51
9.9.	17	4.73	5.11	5.43	5.66	5.26	5.41	4.84	4.88	4.53	4.99	4.79	4.61
12.9.	20	4.81	5.23	5.56	5.81	5.41	5.55	4.99	4.97	4.62	5.09	4.85	4.71
14.9.	23	4.85	5.16	5.54	5.91	5.49	5.64	5.00	4.93	4.66	5.18	4.94	4.76
MAX VALUES		**6.52**	**6.75**	**7.63**	**7.35**	**6.61**	**6.77**	**6.38**	**6.50**	**6.51**	**6.03**	**5.81**	**6.04**
		6.58											

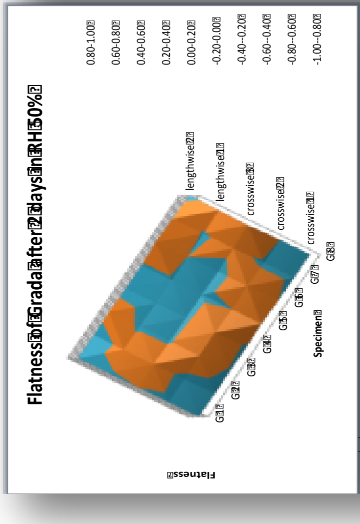
APPENDIX I (2/2) - STABILITY OF THE FORMED PRODUCT

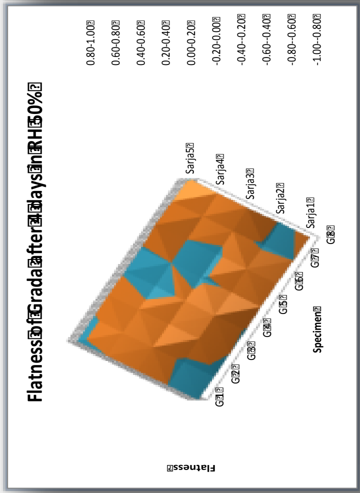
DIAMETER CHANGE

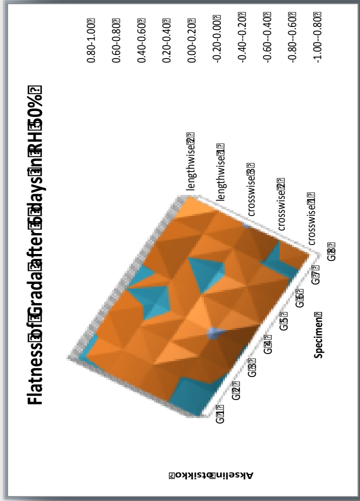
	Specimen	18 S 1 Diameter change (mm)			18 S 2 Diameter change (mm)			18 S 3 Diameter change (mm)			18 S 4 Diameter change (mm)		
28.6.	number of days in the conditions	1	2	3	1	2	3	1	2	3	1	2	3
30.6.	RH 50% 2	0.32	0.35	-0.46	1.65	0.33	0.23	0.32	0.24	0.26	0.13	0.21	0.23
2.7.	4	0.61	0.47	0.41	1.61	0.21	0.41	0.45	0.28	0.31	0.10	0.16	0.25
4.7.	6	0.70	0.66	0.48	1.79	0.44	0.44	0.68	0.47	0.56	0.30	0.42	0.46
6.7.	8	0.90	0.77	0.67	1.93	0.52	0.58	0.74	0.62	0.66	0.38	0.50	0.52
8.7.	10	1.03	0.95	0.78	1.87	0.56	0.62	0.91	0.78	0.86	0.44	0.56	0.54
11.7.	13	1.31	1.14	0.99	2.10	0.81	0.86	1.13	0.92	0.98	0.63	0.75	0.78
13.7.	RH 80% 1	2.09	2.06	2.49	3.43	1.92	2.03	0.99	1.01	1.54	2.38	2.36	2.44
14.7.	2	2.83	2.78	3.29	4.05	2.44	2.72	1.47	1.43	1.68	3.23	3.11	3.09
15.7.	3	3.15	3.23	3.61	4.52	2.83	3.16	1.70	1.74	2.17	3.55	3.39	3.26
18.7.	6	4.44	4.35	4.68	5.44	3.86	4.40	2.53	2.89	3.10	4.53	4.48	4.31
20.7.	8	5.15	5.25	5.53	6.28	4.43	4.86	3.17	3.07	3.66	5.19	5.21	5.09
22.7.	10	5.84	5.77	6.10	6.65	5.01	5.55	3.55	3.61	4.12	5.64	5.66	5.66
25.7.	13	6.79	6.85	7.22	7.36	5.92	6.46	4.36	4.33	4.91	6.52	6.52	6.46
27.7.	15	7.36	7.31	7.67	7.84	6.34	6.93	4.73	4.80	5.26	6.86	7.08	6.80
29.7.	17	7.90	7.85	7.81	8.41	6.84	7.39	5.11	5.22	5.56	7.38	7.51	7.25
1.8.	20	8.47	8.49	8.54	8.81	7.30	7.82	5.62	5.66	6.17	7.66	7.85	7.79
3.8.	RH 30% 1	7.96	8.23	7.85	7.09	5.89	6.29	5.82	6.11	6.29	5.96	6.55	6.22
4.8.	2	7.76	7.91	7.69	6.95	5.82	6.08	5.75	5.91	6.22	5.78	6.22	5.91
5.8.	3	7.35	7.55	7.19	6.70	5.47	5.67	5.58	5.82	6.04	5.48	5.96	5.57
8.8.	6	6.59	6.86	6.58	6.11	5.12	5.26	5.25	5.53	5.70	4.98	5.40	4.89
10.8.	8	6.21	6.71	6.18	5.80	4.81	4.87	4.98	5.31	5.48	4.68	5.08	4.64
12.8.	10	6.07	6.32	6.20	5.54	4.58	4.61	5.03	5.24	5.32	4.47	4.94	4.49
15.8.	13	5.70	6.08	6.00	5.36	4.40	4.39	4.66	5.18	5.31	4.26	4.66	4.00
17.8.	15	5.40	5.88	5.75	5.17	4.24	4.19	4.56	4.99	5.19	4.14	4.33	3.95
19.8.	17	5.25	5.74	5.46	5.12	4.11	4.15	4.46	4.91	5.07	3.92	4.19	3.77
22.8.	20	5.22	5.67	5.41	5.00	4.03	3.97	4.52	4.86	5.12	3.78	4.19	3.62
23.8.	RH 50% 0	5.22	5.74	5.55	5.23	4.17	3.98	4.22	4.77	4.97	3.79	4.12	3.51
24.8.	1	5.35	5.81	5.54	5.44	4.28	4.29	4.44	4.79	5.04	4.17	4.52	4.01
25.8.	2	5.64	5.86	5.90	5.53	4.32	4.43	4.48	4.82	5.13	4.36	4.55	4.05
26.8.	3	5.52	5.93	5.73	5.58	4.40	4.37	4.66	4.89	5.16	4.44	4.65	4.13
29.8.	6	5.86	6.13	6.12	5.78	4.60	4.64	4.82	4.98	5.28	4.54	4.70	4.25
31.8.	8	5.86	6.20	6.11	5.94	4.62	4.78	4.77	5.02	5.34	4.64	4.83	4.40
2.9.	10	6.06	6.29	6.41	5.94	4.62	4.79	4.95	5.14	5.41	4.80	4.98	4.52
5.9.	13	6.07	6.32	6.30	6.01	4.84	4.86	4.95	5.14	5.54	4.82	4.97	4.55
6.9.	14	6.02	6.40	6.25	6.04	4.64	4.90	5.00	5.20	5.50	4.76	4.96	4.61
9.9.	17	6.14	6.41	6.50	6.00	4.78	4.88	5.10	5.27	5.56	4.81	4.96	4.61
12.9.	20	6.25	6.42	6.40	6.04	4.75	4.96	5.14	5.34	5.67	4.86	5.07	4.62
14.9.	23	6.23	6.43	6.55	6.10	4.89	4.99	5.12	5.26	5.61	4.93	5.03	4.72
MAX VALUES		**8.47**	**8.49**	**8.54**	**8.81**	**7.30**	**7.82**	**5.82**	**6.11**	**6.29**	**7.66**	**7.85**	**7.79**
		7.58											

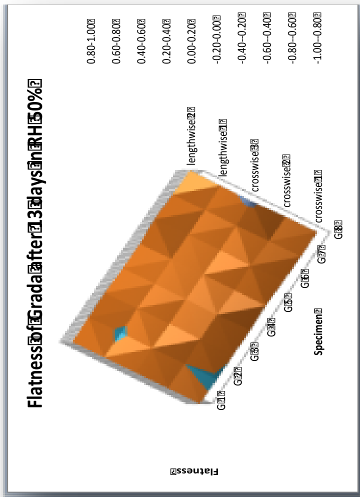
		B1 Diameter change (mm)			B2 Diameter change (mm)		
		1	2	3	1	2	3
19.8.	1	-0.10	-0.28	-0.47	0.09	-0.11	-0.1
22.8.	2	0.34	0.33	0.17	0.76	0.53	0.63
23.8.	3	0.92	0.72	0.74	1.13	1.01	1.16
24.8.	6	1.16	0.92	0.91	1.47	1.24	1.34
25.8.	8	0.85	0.78	0.87	1.84	1.62	1.82
26.8.	9	1.46	1.33	1.31	1.55	1.45	1.5
29.8	10	1.35	1.26	1.41	2.07	1.92	2.02
31.8.	13	1.55	1.46	1.58	2.11	2.1	2.18
2.9	15	2.06	1.89	1.92	1.94	1.89	1.97
5.9.	17	2.02	1.91	1.94	2.19	2.16	2.18
6.9.	20	2.1	1.94	2.11	2.34	2.29	2.32
9.9.	21	1.57	1.75	1.72	2.8	2.77	2.88
12.9.	22	1.92	1.9	2.06	2.82	2.66	2.8
14.9.	23	2.05	1.98	1.98	2.76	2.75	2.87
		2.10	1.98	2.11	2.82	2.77	2.88

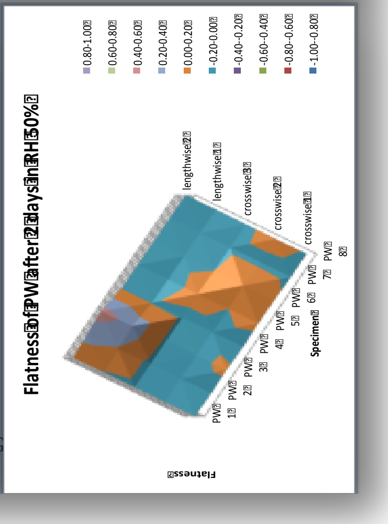
APPENDIX II – FLATNESS (1/6)

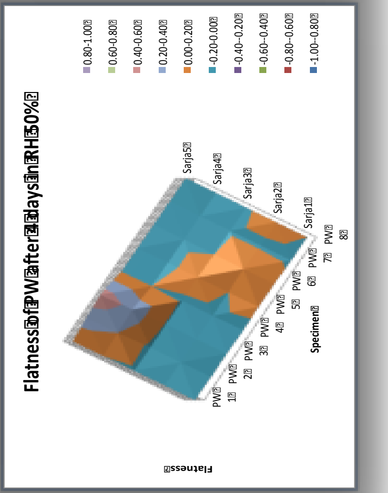


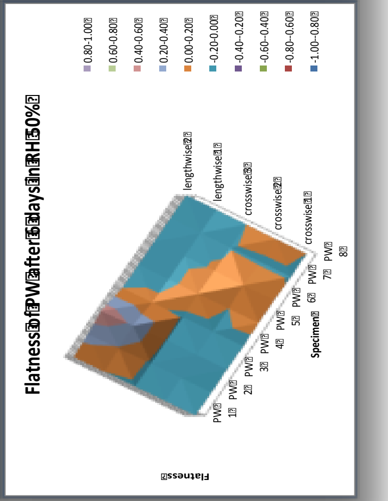


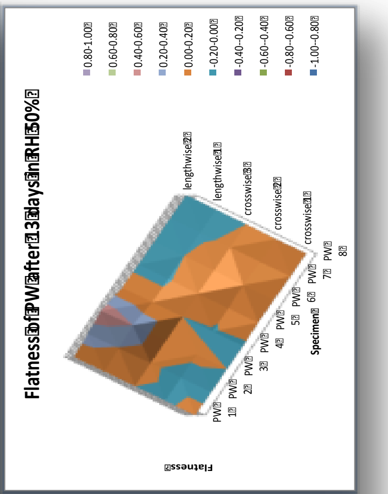






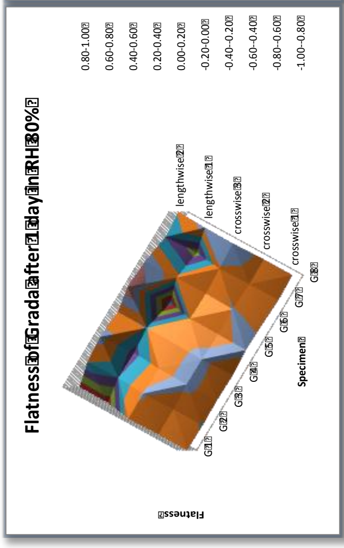


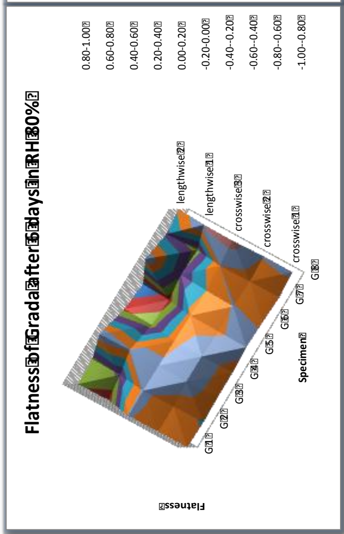


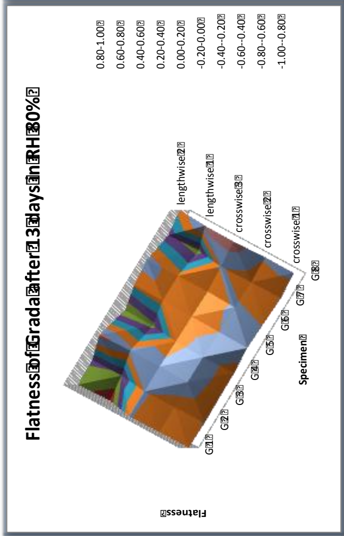


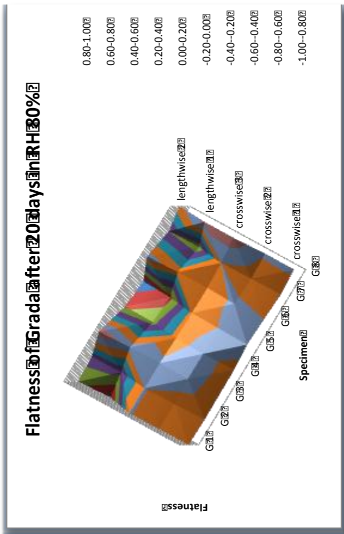
G – Grada
PW – conventional plywood

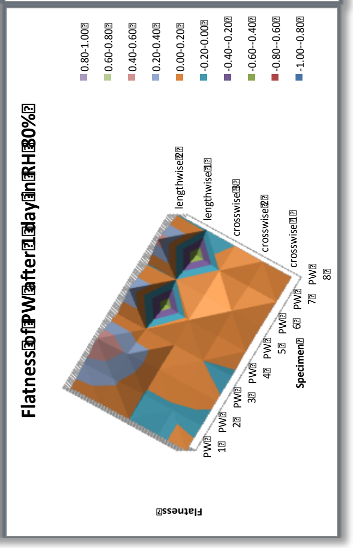
APPENDIX II – FLATNESS (2/6)

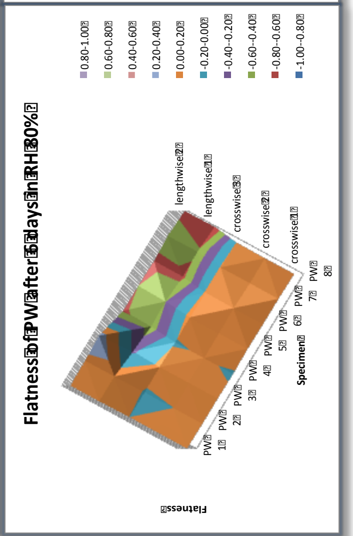


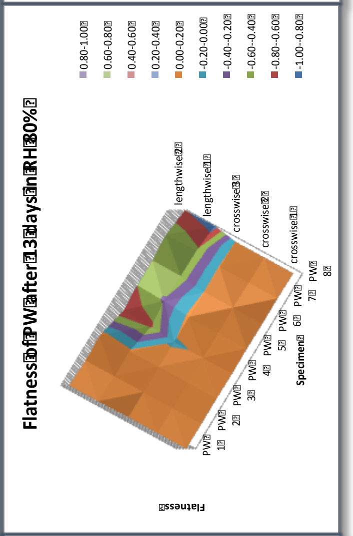


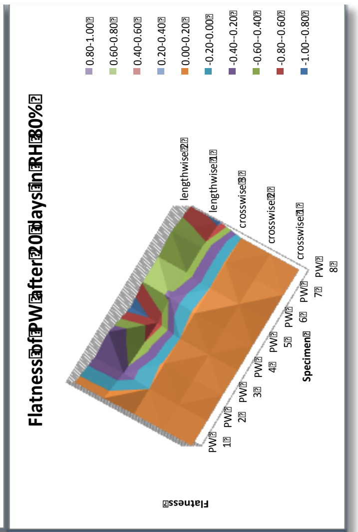




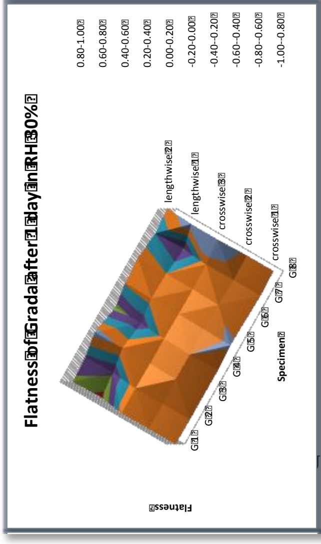


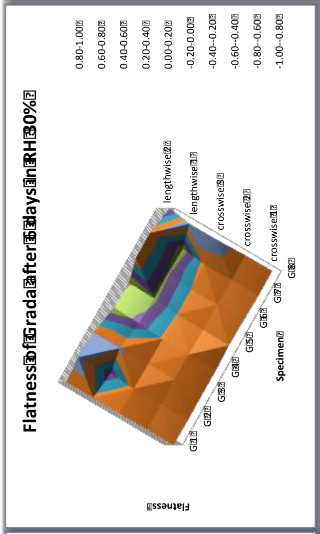


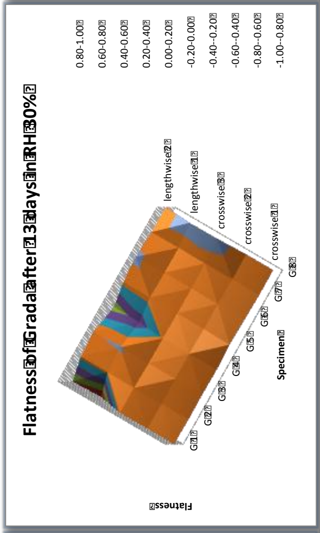


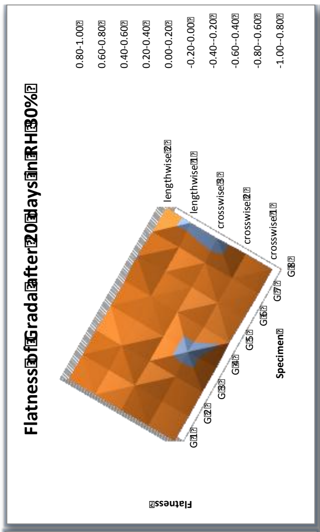


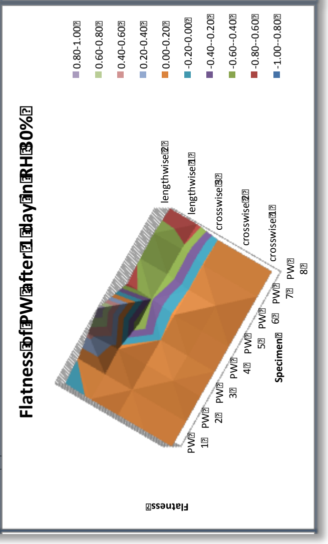
APPENDIX II – FLATNESS (3/6)

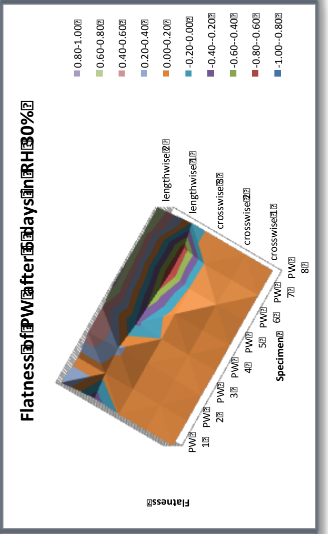


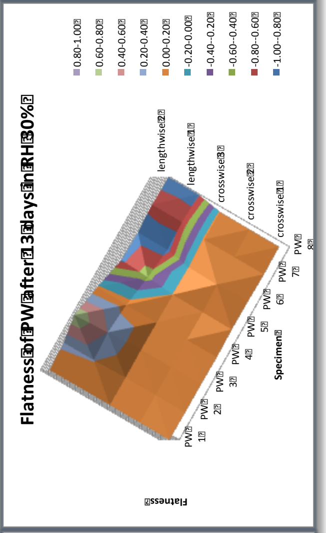


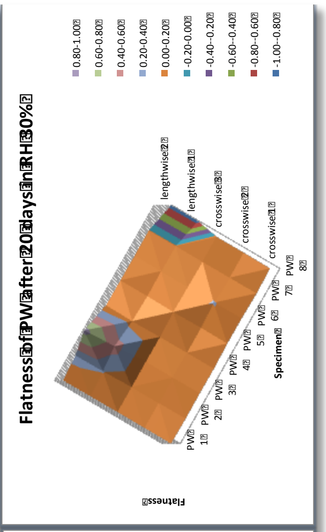












G – Grada
PW – conventional plywood

APPENDIX II – FLATNESS (4/6)

	30.6.					2.7.					4.7.					6.7.					8.7.					11.7.				
	gap (mm)					gap (mm)					gap (mm)					gap (mm)					gap (mm)					gap (mm)				
	crosswise			lengthwise		crosswise			lengthwise		crosswise			lengthwise		crosswise			lengthwise		crosswise			lengthwise		crosswise			lengthwise	
	1	2	3	1	2	1	2	3	1	2	1	2	3	1	2	1	2	3	1	2	1	2	3	1	2	1	2	3	1	2
G 1	-0.02	-0.02	0.00	-0.01	-0.04	-0.01	0.00	0.01	0.00	-0.01	0.00	0.00	0.03	0.00	-0.01	0.01	0.00	0.02	0.00	-0.02	0.01	0.02	0.04	0.02	0.00	0.02	0.01	0.03	0.03	0.01
G 2	-0.06	-0.03	0.06	0.03	-0.06	-0.04	-0.02	0.07	0.04	-0.01	-0.04	-0.01	0.07	0.05	-0.01	-0.05	-0.02	0.08	0.04	-0.01	-0.02	0.00	0.09	0.06	0.01	-0.02	0.00	0.09	-0.02	0.07
G 3	-0.01	0.09	-0.01	-0.01	0.05	0.00	0.09	0.00	0.03	0.06	0.00	0.11	0.00	0.01	0.08	0.00	0.11	0.00	0.03	0.08	0.01	0.12	0.01	0.05	0.09	0.01	0.13	0.01	0.05	0.12
G 4	-0.02	0.12	-0.02	-0.04	-0.03	-0.01	0.12	0.02	-0.04	-0.01	-0.02	0.24	0.03	-0.03	0.00	-0.02	0.19	0.03	-0.04	-0.01	0.00	0.15	0.04	-0.01	0.00	0.00	0.15	0.05	0.00	0.01
G 5	0.09	0.00	-0.03	-0.02	-0.02	0.11	0.01	-0.02	0.00	-0.02	0.11	0.02	0.00	0.01	-0.01	0.12	0.03	0.00	0.02	0.00	0.13	0.04	0.00	0.02	0.00	0.13	0.04	0.03	0.02	0.00
G 6	0.00	0.08	-0.04	0.00	0.17	0.10	0.11	-0.02	0.00	0.17	0.01	0.10	-0.03	0.00	0.19	0.03	0.11	-0.03	0.01	0.18	0.02	0.12	-0.02	0.01	0.19	0.04	0.15	0.00	0.01	0.19
G 7	-0.02	-0.02	0.03	-0.01	0.09	0.00	-0.02	0.04	0.03	0.08	-0.01	-0.01	0.05	0.00	0.07	-0.01	-0.01	0.04	0.02	0.08	0.00	0.01	0.05	0.01	0.09	0.00	0.00	0.06	0.02	0.08
G 8	0.00	0.00	0.20	0.06	-0.03	0.01	-0.01	0.20	0.11	-0.01	0.02	0.00	0.22	0.11	0.00	0.02	0.00	0.21	0.10	-0.01	0.04	0.01	0.23	0.12	0.01	0.04	0.01	0.24	0.15	0.01
PW 1	-0.02	-0.05	-0.05	-0.01	0.04	0.00	-0.03	-0.03	0.00	0.05	0.00	-0.03	-0.04	0.00	0.06	0.00	-0.03	-0.03	0.00	0.06	0.01	-0.01	-0.01	0.01	0.08	0.02	-0.01	0.00	0.05	0.08
PW 2	-0.06	-0.05	-0.05	0.18	0.28	-0.04	-0.02	-0.04	0.20	0.30	-0.04	-0.03	-0.03	0.18	0.28	-0.04	-0.03	-0.03	0.18	0.26	-0.02	-0.03	-0.02	0.21	0.30	-0.02	-0.02	0.01	0.19	0.29
PW 3	0.02	-0.02	-0.03	0.33	0.49	0.00	0.00	-0.01	0.34	0.53	0.00	0.00	-0.01	0.37	0.55	-0.04	0.00	-0.01	0.37	0.53	0.00	0.00	0.00	0.30	0.58	0.00	0.01	0.01	0.40	0.55
PW 4	-0.06	-0.03	-0.03	-0.01	-0.01	-0.05	-0.03	-0.02	0.00	0.00	-0.04	-0.03	-0.02	0.02	0.00	-0.04	-0.02	-0.01	0.01	0.01	-0.03	-0.01	0.00	0.02	0.02	-0.02	-0.01	0.00	0.02	0.02
PW 5	0.03	0.00	0.04	-0.05	-0.04	0.05	0.00	0.06	-0.03	-0.03	0.04	0.00	0.06	-0.03	-0.03	0.04	0.01	0.09	-0.03	-0.02	0.06	0.02	0.07	-0.02	-0.02	0.07	0.02	0.08	-0.01	-0.01
PW 6	0.03	0.14	0.00	-0.03	-0.05	0.05	0.14	0.00	-0.03	-0.05	0.04	0.14	0.01	-0.03	-0.03	0.04	0.14	0.03	-0.02	-0.03	0.06	0.15	0.07	0.00	-0.03	0.06	0.15	0.03	0.00	-0.02
PW 7	-0.04	-0.03	-0.03	-0.05	-0.05	-0.03	-0.02	-0.02	-0.04	-0.05	-0.02	-0.02	-0.01	-0.03	-0.04	-0.01	-0.01	-0.01	-0.03	-0.04	0.01	-0.01	0.00	-0.02	-0.03	0.00	0.00	0.01	-0.01	-0.02
PW 8	-0.01	0.04	-0.02	-0.06	-0.05	0.00	0.04	-0.01	-0.05	-0.04	0.00	0.05	0.00	-0.05	-0.04	0.00	0.04	-0.01	-0.03	-0.04	0.01	0.05	0.00	-0.04	-0.03	0.01	0.04	0.00	-0.02	-0.02

	13.7. (1 day at RH80%)					14.7. (2 days at RH80%)					15.7.					18.7.					20.7.					22.7.					25.7.					27.7.					29.7.					1.8.				
	gap (mm)					gap (mm)					gap (mm)					gap (mm)					gap (mm)					gap (mm)					gap (mm)					gap (mm)					gap (mm)					gap (mm)				
	crosswise			lengthwise		crosswise			lengthwise		crosswise			lengthwise		crosswise			lengthwise		crosswise			lengthwise		crosswise			lengthwise		crosswise			lengthwise		crosswise			lengthwise		crosswise			lengthwise		crosswise			lengthwise	
	1	2	3	1	2	1	2	3	1	2	1	2	3	1	2	1	2	3	1	2	1	2	3	1	2	1	2	3	1	2	1	2	3	1	2	1	2	3	1	2	1	2	3	1	2	1	2	3	1	2
G 1	0.05	0.03	0.16	-0.73	-0.76	0.07	0.06	0.20	0.05	-0.03	0.07	0.07	0.21	-0.74	-0.70	0.08	0.09	0.22	-0.74	-0.55	0.07	0.09	0.21	0.06	0.03	0.07	0.11	0.24	0.06	0.04	0.07	0.10	0.21	-0.78	-0.47	0.08	0.11	0.25	0.08	0.04	0.07	0.10	0.21	0.07	0.04	0.07	0.11	0.21	-0.85	-0.52
G 2	-0.01	0.05	0.22	-0.20	0.01	-0.02	0.06	0.23	0.06	0.02	-0.01	0.08	0.25	-0.41	-0.51	-0.02	0.08	0.25	-0.38	-0.47	-0.02	0.09	0.26	0.04	0.02	-0.02	0.09	0.24	0.02	0.05	-0.01	0.09	0.22	-0.41	-0.38	-0.03	0.10	0.23	0.09	0.07	-0.01	0.09	0.22	0.04	0.05	0.00	0.09	0.21	-0.36	-0.32
G 3	0.08	0.26	0.14	-0.28	0.29	0.09	0.27	0.14	0.12	0.21	0.08	0.32	0.20	0.14	0.29	0.08	0.34	0.22	0.22	0.37	0.08	0.35	0.24	0.27	0.43	0.06	0.34	0.23	0.27	0.45	0.06	0.34	0.24	0.28	0.49	0.04	0.33	0.24	0.30	0.51	0.06	0.34	0.24	0.28	0.49	0.05	0.32	0.23	0.30	0.55
G 4	0.02	0.26	0.13	-0.01	0.01	0.06	0.28	0.15	-0.58	-0.65	0.06	0.31	0.15	-0.58	-0.65	0.10	0.33	0.16	-0.49	-0.65	0.10	0.33	0.15	0.03	0.02	0.09	0.33	0.15	0.03	0.03	0.09	0.32	0.13	-0.47	-0.61	0.08	0.32	0.13	0.07	0.01	0.09	0.32	0.13	0.07	0.03	0.09	0.30	0.11	-0.48	-0.63
G 5	0.26	0.13	0.05	-0.91	0.60	0.27	0.14	0.05	-0.60	-0.91	0.28	0.16	0.05	0.04	0.01	0.29	0.17	0.08	-0.70	-1.01	0.32	0.18	0.06	0.08	0.02	0.33	0.20	0.09	0.09	0.03	0.34	0.20	0.08	0.10	0.04	0.35	0.21	0.07	0.08	0.03	0.34	0.20	0.08	0.10	0.04	0.35	0.21	0.06	-0.68	-0.93
G 6	0.17	0.21	0.00	0.07	0.39	0.18	0.21	0.00	0.09	0.43	0.16	0.23	0.00	-0.27	0.43	0.17	0.21	0.00	-0.36	0.36	0.17	0.25	0.00	0.11	0.41	0.18	0.24	0.01	0.11	0.37	0.18	0.24	0.01	0.09	0.31	0.19	0.24	0.01	0.13	0.36	0.18	0.24	0.01	0.09	0.31	0.20	0.25	0.03	0.10	0.30
G 7	0.01	0.06	0.18	-0.50	-0.21	0.01	0.07	0.19	-0.41	-0.14	0.01	0.09	0.21	0.03	0.06	0.00	0.09	0.20	-0.49	-0.26	0.00	0.10	0.22	0.05	0.05	0.01	0.08	0.22	0.05	0.05	0.00	0.08	0.22	-0.49	-0.34	0.00	0.08	0.20	0.03	0.04	0.00	0.08	0.22	0.03	0.05	0.01	0.07	0.20	-0.53	-0.40
G 8	0.16	0.13	0.37	0.28	0.02	0.19	0.14	0.40	0.36	0.03	0.21	0.18	0.43	0.33	0.03	0.24	0.21	0.49	0.43	0.04	0.26	0.22	0.53	0.47	0.06	0.27	0.25	0.53	0.53	0.07	0.26	0.22	0.52	0.46	0.08	0.24	0.22	0.52	0.46	0.08	0.26	0.22	0.52	0.46	0.08	0.24	0.23	0.52	0.50	0.12
																												0.00																						
PW 1	0.02	-0.01	0.00	0.09	0.12	0.03	0.00	0.00	0.10	0.14	0.03	0.00	0.00	0.11	0.13	0.02	0.01	0.00	0.11	0.11	0.03	0.01	0.00	0.09	0.10	0.02	0.01	0.00	0.11	0.11	0.03	0.01	0.00	0.13	0.12	0.02	0.01	0.00	0.11	0.10	0.03	0.01	0.00	0.13	0.12	0.03	0.02	0.01	0.14	0.12
PW 2	-0.02	-0.01	-0.01	0.24	0.34	0.00	0.00	-0.01	0.27	0.35	-0.01	0.00	-0.01	0.13	0.23	0.00	0.00	-0.01	0.12	0.16	-0.01	0.00	-0.01	0.07	0.08	-0.01	0.00	0.00	0.04	0.04	0.00	0.00	0.00	0.02	0.03	-0.01	0.00	0.00	0.03	0.04	0.00	0.00	0.00	0.02	0.03	0.00	0.00	0.00	-0.34	-0.36
PW 3	0.01	0.03	0.04	0.37	0.61	0.02	0.05	0.06	0.28	0.53	0.02	0.05	0.08	0.20	0.51	0.02	0.04	0.05	-0.23	0.32	0.02	0.04	0.05	0.06	0.23	0.03	0.04	0.05	0.05	0.16	0.03	0.03	0.04	0.05	0.12	0.03	0.02	0.05	0.05	0.10	0.03	0.03	0.04	0.05	0.12	0.04	0.02	0.04	-0.56	-0.21
PW 4	-0.03	0.00	0.00	0.02	0.03	-0.02	0.00	0.00	-0.35	-0.44	-0.02	0.01	0.00	0.01	0.02	-0.01	0.01	-0.01	-0.51	-0.63	0.00	0.01	0.00	0.01	0.01	-0.01	0.01	0.00	0.00	0.00	0.00	0.01	-0.01	-0.64	-0.79	-0.01	0.01	-0.01	0.01	0.01	0.00	0.01	-0.01	0.01	0.00	0.00	0.01	0.00	-0.73	-0.94
PW 5	0.09	0.06	0.10	-0.55	0.38	0.09	0.07	0.10	-0.49	-0.62	0.09	0.06	0.09	-0.40	-0.58	0.07	0.05	0.07	-0.41	-0.60	0.07	0.05	0.07	0.01	0.01	0.05	0.04	0.06	0.00	0.00	0.05	0.03	0.05	-0.37	-0.60	0.05	0.03	0.05	0.01	0.00	0.05	0.03	0.05	0.00	0.00	0.04	0.03	0.05	-0.36	-0.58
PW 6	0.10	0.19	0.05	0.00	-0.01	0.08	0.18	0.05	0.00	-0.02	0.07	0.18	0.04	-0.60	-0.63	0.04	0.12	0.02	-0.65	-0.67	0.03	0.11	0.02	-0.01	-0.01	0.03	0.10	0.03	0.00	0.00	0.02	0.09	0.01	-0.53	-0.60	0.04	0.10	0.02	0.00	0.00	0.02	0.09	0.01	0.00	0.00	0.03	0.07	0.01	-0.53	-0.59
PW 7	0.05	0.01	0.02	-0.58	0.51	0.05	0.01	0.02	-0.65	-0.54	0.05	0.02	0.01	-0.63	-0.51	0.05	0.01	0.02	-0.57	-0.46	0.06	0.02	0.03	0.00	0.02	0.05	0.01	0.03	0.00	0.02	0.05	0.01	0.02	-0.56	-0.40	0.05	0.01	0.02	0.01	0.04	0.05	0.01	0.02	0.00	0.04	0.05	0.02	0.03	-0.53	-0.40
PW 8	0.03	0.08	0.00	-0.03	-0.02	0.03	0.11	0.00	-0.64	-0.58	0.01	0.09	0.00	-0.79	-0.70	0.00	0.04	0.00	-0.78	-0.67	0.00	0.03	0.00	-0.01	-0.01	0.00	0.03	0.00	-0.01	-0.01	0.00	0.00	0.00	-0.89	-0.79	0.00	0.00	0.00	-0.01	-0.01	0.00	0.00	0.00	-0.01	-0.01	0.01	0.00	0.00	-0.85	-0.75

APPENDIX II – FLATNESS (5/6)

3.8. one day at RH30%					4.8. two days at RH30%					5.8. RH30%					8.8. RH30%					10.8. RH30%				
gap (mm)					gap (mm)					gap (mm)					gap (mm)					gap (mm)				
crosswise			lengthwise		crosswise			lengthwise		crosswise			lengthwise		crosswise			lengthwise		crosswise			lengthwise	
1	2	3	1	2	1	2	3	1	2	1	2	3	1	2	1	2	3	1	2	1	2	3	1	2
0.05	0.07	0.11	-0.67	-0.45	0.06	0.06	0.11	0.06	0.05	0.04	0.05	0.08	0.06	0.03	0.04	0.03	0.08	0.06	0.05	0.04	0.04	0.09	0.07	0.04
0.00	0.03	0.13	-0.37	-0.25	0.01	0.02	0.11	0.04	0.05	0.00	0.02	0.11	0.02	0.04	0.00	0.01	0.09	-0.33	0.34	0.00	0.00	0.12	0.05	0.04
0.02	0.18	0.06	0.17	0.29	0.03	0.14	0.04	0.27	0.30	0.02	0.12	0.03	0.18	0.22	0.04	0.09	0.03	0.23	0.20	0.04	0.09	0.04	0.22	0.18
0.02	0.20	0.08	-0.33	-0.48	0.01	0.17	0.04	0.00	0.02	0.02	0.16	0.03	0.00	0.00	0.03	0.12	0.03	-0.34	-0.55	0.01	0.11	0.03	0.02	0.02
0.23	0.12	0.03	0.09	0.03	0.22	0.11	0.04	0.08	0.05	0.20	0.08	0.02	0.07	0.05	0.18	0.05	0.00	-0.46	-0.62	0.17	0.06	0.04	0.05	0.03
0.12	0.17	0.02	0.00	0.17	0.11	0.17	0.01	0.03	0.18	0.10	0.15	0.00	0.04	0.14	0.10	0.10	0.00	-0.43	0.18	0.09	0.10	0.00	0.00	0.21
0.01	0.03	0.12	-0.42	-0.20	0.02	0.03	0.11	0.04	0.04	0.01	0.03	0.09	0.02	0.04	0.01	0.02	0.08	-0.52	0.18	-0.01	0.02	0.10	0.02	0.06
0.13	0.14	0.41	0.37	0.08	0.09	0.11	0.38	0.43	0.09	0.08	0.09	0.36	0.38	0.07	0.05	0.08	0.33	0.36	-0.46	0.04	0.07	0.31	0.35	0.07
0.01	0.01	0.00	0.05	-0.18	0.01	0.00	0.00	0.06	0.10	0.03	0.01	0.01	0.03	0.06	0.02	0.01	0.02	-0.31	0.42	0.02	0.01	0.01	0.05	0.06
0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.05	0.05	0.00	0.00	0.00	0.03	0.03	0.00	0.00	0.00	0.09	0.09	0.01	0.00	0.01	0.11	0.10
0.03	0.06	0.02	0.11	0.47	0.03	0.02	0.02	0.10	0.44	0.03	0.03	0.02	0.05	0.34	0.03	0.02	0.03	0.24	0.58	0.03	0.02	0.02	0.31	0.64
0.00	0.01	0.00	-0.57	1.05	0.00	0.02	0.00	0.02	0.01	0.00	0.01	0.01	0.03	0.02	0.00	0.01	0.01	-0.24	0.58	0.01	0.02	0.01	0.08	0.04
0.02	0.03	0.05	-0.42	-0.73	0.04	0.04	0.05	0.00	0.00	0.04	0.03	0.07	0.00	0.00	0.04	0.03	0.11	-0.51	0.88	0.07	0.02	0.09	0.01	0.01
0.02	0.07	0.01	-0.59	-0.56	0.04	0.07	0.02	0.01	0.00	0.03	0.09	0.02	0.01	0.00	0.06	0.11	0.03	-0.80	0.82	0.07	0.14	0.06	0.02	0.00
0.02	0.02	0.02	-0.57	-0.48	0.02	0.02	0.02	0.00	0.02	0.03	0.02	0.01	0.01	0.01	0.03	0.01	0.01	-0.73	0.72	0.02	0.01	0.01	0.01	0.01
0.00	0.00	0.00	-0.73	-0.71	0.00	0.01	0.01	-0.01	0.00	0.01	0.01	0.00	-0.01	0.00	0.01	0.02	0.01	-0.01	0.82	0.03	0.03	0.01	-0.01	0.00

G – Grada
PW – conventional plywood

12.8. RH30%					15.8. RH30%					19.8. RH30%					22.8. RH30%				
gap (mm)					gap (mm)					gap (mm)					gap (mm)				
crosswise			lengthwise		crosswise			lengthwise		crosswise			lengthwise		crosswise			lengthwise	
1	2	3	1	2	1	2	3	1	2	1	2	3	1	2	1	2	3	1	2
0.04	0.03	0.09	0.05	0.04	0.05	0.04	0.10	-0.82	-0.62	0.03	0.02	0.11	0.07	0.06	0.04	0.03	0.10	0.06	0.02
0.00	0.01	0.11	0.04	0.07	0.00	0.01	0.11	0.05	0.05	0.00	0.00	0.11	0.04	0.06	0.00	0.00	0.13	0.04	0.04
0.03	0.08	0.03	0.21	0.17	0.05	0.08	0.03	0.22	0.19	0.05	0.07	0.03	0.21	0.14	0.04	0.07	0.03	0.18	0.12
0.03	0.11	0.03	0.01	0.03	0.01	0.11	0.03	-0.32	-0.51	0.02	0.11	0.03	0.01	0.00	0.01	0.31	0.03	0.01	0.00
0.18	0.06	0.20	0.07	0.04	0.17	0.05	0.01	0.08	0.05	0.18	0.04	0.02	0.07	0.05	0.17	0.04	0.04	0.07	0.03
0.06	0.10	0.00	0.03	0.21	0.08	0.09	0.01	0.02	0.25	0.08	0.09	0.03	0.01	0.27	0.07	0.09	0.00	0.01	0.21
0.01	0.03	0.09	0.04	0.06	0.01	0.02	0.09	0.03	0.06	0.02	0.03	0.09	0.01	0.08	0.01	0.02	0.09	0.01	0.05
0.04	0.05	0.32	0.35	0.05	0.04	0.05	0.33	0.37	0.06	0.05	0.05	0.32	0.38	0.06	0.04	0.03	0.32	0.29	0.03
0.03	0.02	0.01	0.04	0.05	0.03	0.01	0.01	0.04	0.07	0.03	0.01	0.02	0.04	0.07	0.04	0.01	0.01	0.04	0.06
0.00	0.00	0.00	0.13	0.14	0.01	0.00	0.00	0.21	0.24	0.01	0.01	0.01	0.23	0.28	0.00	0.00	0.01	0.21	0.27
0.04	0.02	0.03	0.37	0.73	0.03	0.03	0.04	0.40	0.77	0.00	0.03	0.03	0.49	0.87	0.03	0.04	0.03	0.50	0.88
0.00	0.01	0.02	0.07	0.03	0.00	0.02	0.03	0.11	0.04	0.00	0.02	0.03	0.13	0.05	0.01	0.02	0.02	0.12	0.04
0.08	0.03	0.11	0.01	0.01	0.09	0.02	0.01	-0.48	-0.85	0.09	0.03	0.03	0.01	0.01	0.11	0.03	0.13	0.01	0.01
0.08	0.16	0.06	0.02	0.00	0.08	0.17	0.00	-0.89	-0.93	0.11	0.19	0.07	0.04	0.00	0.11	0.21	0.08	0.05	0.00
0.02	0.02	0.02	0.00	0.01	0.02	0.03	0.04	-0.75	-0.74	0.03	0.02	0.02	0.01	0.01	0.02	0.02	0.03	0.02	0.01
0.04	0.04	0.02	0.00	0.00	0.08	0.06	0.03	-0.84	-0.85	0.09	0.07	0.05	0.00	-0.01	0.11	0.04	0.06	-0.88	-0.89

FG – formed Grada
UFG – unsanded formed Grada
FB – formed beech

APPENDIX II – FLATNESS (6/6)

23.8. RH50%					24.8. RH50%					25.8. RH50%				
gap (mm)					gap (mm)					gap (mm)				
crosswise			lengthwise		crosswise			lengthwise		crosswise			lengthwise	
1	2	3	1	2	1	2	3	1	2	1	2	3	1	2
0.02	0.02	0.11	0.06	0.03	0.03	0.03	0.12	-0.79	-0.52	-0.02	-0.04	0.05	-0.01	-0.03
0.00	0.00	0.01	0.04	0.05	-0.01	0.00	0.13	-0.36	-0.34	-0.08	-0.07	0.08	-0.04	-0.04
0.04	0.08	0.04	0.17	0.13	0.04	0.08	0.05	0.18	0.16	-0.02	0.03	0.00	0.10	0.09
0.00	0.13	0.04	0.00	0.01	0.00	0.11	0.04	-0.32	-0.47	-0.05	0.07	-0.02	-0.08	-0.08
0.18	0.05	0.05	0.05	0.04	0.15	0.05	0.05	0.06	0.05	0.13	-0.03	-0.05	0.00	-0.03
0.07	0.09	0.01	0.01	0.26	0.07	0.07	0.00	-0.37	0.28	0.01	0.01	-0.06	-0.05	0.19
0.02	0.04	0.09	0.02	0.07	0.03	0.02	0.12	-0.49	-0.19	0.00	-0.06	0.01	-0.06	-0.04
0.04	0.04	0.32	0.27	0.03	0.06	0.05	0.34	0.30	0.05	0.00	-0.01	0.28	0.23	-0.04
0.03	0.01	0.01	0.04	0.08	0.02	0.01	0.01	-0.33	-0.36	-0.02	-0.06	-0.05	-0.02	0.02
0.00	0.01	0.00	0.20	0.22	0.00	0.00	0.01	0.27	0.36	-0.07	-0.07	-0.07	0.17	0.26
0.02	0.03	0.04	0.51	0.88	0.02	0.03	0.04	0.48	0.84	-0.04	-0.03	-0.03	0.34	0.70
0.01	0.02	0.04	0.13	0.04	0.00	0.01	0.02	-0.13	-0.40	-0.08	-0.08	-0.07	0.00	-0.04
0.11	0.01	0.13	0.01	0.02	0.10	0.04	0.14	-0.57	-0.86	0.03	-0.04	0.06	-0.06	-0.06
0.12	0.01	0.08	0.04	0.01	0.12	0.23	0.07	-0.86	-0.92	0.04	0.15	0.00	-0.04	-0.08
0.02	0.03	0.01	0.01	0.02	0.02	0.01	0.01	-0.77	-0.76	-0.06	-0.06	-0.07	-0.07	-0.07
0.11	0.02	0.05	-0.91	-0.96	0.10	0.11	0.03	-0.89	-0.88	0.01	0.02	-0.05	-0.09	-0.08

26.8. RH50%					29.8. RH50%				
gap (mm)					gap (mm)				
crosswise			lengthwise		crosswise			lengthwise	
1	2	3	1	2	1	2	3	1	2
-0.02	-0.06	0.05	-0.04	-0.04	-0.02	-0.04	0.06	-0.73	-0.44
-0.07	-0.08	0.07	-0.04	-0.02	-0.09	-0.08	0.07	-0.26	-0.22
-0.03	0.04	0.00	0.10	0.11	-0.03	0.06	-0.01	0.13	0.12
-0.07	0.06	-0.01	-0.07	-0.04	-0.05	0.07	-0.01	-0.25	-0.40
0.11	-0.01	-0.07	0.00	-0.03	0.09	-0.02	-0.02	-0.41	-0.64
0.03	0.03	-0.07	-0.08	0.17	0.00	0.01	-0.08	-0.28	0.18
-0.08	-0.05	0.04	-0.07	-0.03	-0.07	-0.05	0.03	-0.43	-0.12
0.00	0.00	0.28	0.25	-0.01	-0.01	-0.01	0.29	0.27	-0.42
-0.04	-0.05	-0.07	0.00	0.02	-0.05	-0.07	-0.06	-0.17	-0.21
-0.07	-0.07	-0.08	0.19	0.28	-0.07	-0.06	-0.07	0.16	0.23
-0.05	-0.03	-0.03	0.33	0.72	-0.05	-0.03	-0.03	0.27	0.68
-0.08	-0.05	-0.05	0.00	-0.04	-0.08	-0.06	-0.06	-0.20	-0.41
0.03	-0.03	0.05	-0.06	-0.06	0.03	-0.04	0.05	-0.49	-0.79
0.04	0.14	-0.01	-0.03	-0.03	0.02	0.12	0.00	-0.73	-0.81
-0.07	-0.05	-0.05	-0.06	-0.06	-0.08	-0.06	-0.05	-0.67	-0.66
0.00	0.01	-0.04	-0.08	-0.08	-0.01	0.01	-0.05	-0.81	-0.80

31.8. RH50%					2.9. RH50%					5.9. RH50%					6.9.				
gap (mm)					gap (mm)					gap (mm)					gap (mm)				
crosswise			lengthwise		crosswise			lengthwise		crosswise			lengthwise		crosswise			lengthwise	
1	2	3	1	2	1	2	3	1	2	1	2	3	1	2	1	2	3	1	2
0.00	-0.01	0.07	0.01	-0.02	0.00	-0.01	0.07	0.01	0.00	0.00	0.00	0.07	0.02	0.00	0.00	-0.01	0.06	0.01	-0.01
-0.05	-0.05	0.08	0.00	0.00	-0.05	-0.04	0.09	0.00	0.01	-0.05	-0.03	0.09	0.01	0.00	-0.04	-0.03	0.10	0.00	0.00
0.01	0.07	0.02	0.18	0.18	0.00	0.07	0.02	0.15	0.18	0.00	0.08	0.02	0.16	0.17	0.00	0.07	0.01	0.16	0.16
-0.03	0.10	0.00	-0.03	-0.03	-0.02	0.10	0.00	-0.04	-0.02	-0.02	0.10	0.00	-0.28	-0.43	-0.02	0.09	0.00	-0.04	-0.02
0.17	0.00	-0.03	0.00	-0.02	0.16	0.00	-0.01	0.02	-0.02	0.16	0.01	-0.01	0.02	-0.01	0.16	0.00		0.03	0.00
0.02	0.03	-0.05	-0.01	0.19	0.04	0.06	-0.03	-0.02	0.20	0.04	0.06	-0.02	-0.02	0.21	0.04	0.06	-0.03	-0.03	0.19
-0.04	-0.02	0.06	-0.01	0.00	-0.03	-0.01	0.06	0.28	0.00	-0.03	-0.01	0.07	-0.46	-0.14	-0.03	-0.02	0.05	-0.02	0.00
0.05	0.02	0.30	0.31	0.00	0.04	0.02	0.31		0.00	0.06	0.02	0.32	0.32	0.01	0.05	0.02	0.31	0.31	0.00
-0.01	-0.02	-0.04	0.00	0.05	-0.01	-0.04	-0.03	0.00	0.04	-0.01	-0.03	-0.03	0.00	0.04	-0.01	-0.04	-0.03	0.00	0.04
-0.05	-0.04	-0.04	0.14	0.23	-0.04	-0.04	-0.04	0.14	0.24	-0.04	-0.04	-0.04	0.19	0.25	-0.04	-0.04	-0.04	0.16	0.25
-0.02	0.00	-0.02	0.29	0.66	-0.02	0.00	-0.01	0.28	0.68	-0.01	0.00	0.00	0.29	0.68	-0.01	-0.01	-0.01	0.29	0.68
-0.05	-0.04	-0.03	0.00	-0.01	-0.04	-0.03	-0.02	0.01	0.00	-0.04	-0.02	-0.02	-0.15	-0.39	-0.05	-0.03	-0.03	0.02	-0.01
0.05	-0.01	0.07	-0.04	-0.03	0.05	0.00	0.08	-0.04	-0.03	0.04	0.00	0.07	-0.54	-0.82	0.04	-0.01	0.08	-0.04	-0.03
0.03	0.14	0.02	0.00	-0.04	0.04	0.14	0.02	-0.01	-0.05	0.04	0.15	0.02	-79.00	-0.86	0.04	0.14	0.02	-0.01	-0.04
-0.02	-0.04	-0.04	-0.03	-0.02	-0.02	-0.03	-0.03	-0.04	-0.03	-0.02	-0.02	-0.01	-0.69	-0.67	-0.02	-0.02	-0.02	-0.03	-0.02
0.00	0.04	-0.02	-0.05	-0.04	0.00	0.02	-0.02	-0.06	-0.05	0.00	0.04	-0.02	-0.81	-0.86	-0.01	0.02	-0.02	-0.06	-0.04

9.9. RH50%					12.9. RH50%					14.9. RH50%				
gap (mm)					gap (mm)					gap (mm)				
crosswise			lengthwise		crosswise			lengthwise		crosswise			lengthwise	
1	2	3	1	2	1	2	3	1	2	1	2	3	1	2
0.00	-0.02	0.05	0.01	0.00	0.00	-0.02	0.06	0.02	-0.01	0.00	-0.01	0.06	0.02	-0.01
-0.06	-0.06	0.09	0.00	0.00	-0.06	-0.06	0.10	0.00	0.00	-0.07	-0.06	0.08	0.00	0.00
-0.01	0.07	0.01	0.17	0.16	0.00	0.07	0.00	0.15	0.17	0.00	0.06	0.01	0.17	0.17
-0.02	0.09	0.00	-0.05	-0.02	-0.02	0.09	0.00	-0.29	-0.43	-0.04	0.09	0.00	-0.27	-0.42
0.16	0.01	-0.01	0.02	0.00	0.15	0.00	-0.01	0.02	-0.01	0.15	0.00	-0.02	0.03	0.00
0.04	0.05	-0.03	-0.02	0.20	0.03	0.05	-0.04	-0.04	0.18	0.03	0.05	-0.04	-0.03	0.20
-0.04	-0.03	0.06	-0.02	0.01	-0.04	-0.03	0.06	-0.02	0.00	-0.04	-0.03	0.06	-0.02	0.00
0.04	0.01	0.32	0.31	0.00	0.04	0.00	0.31	0.31	0.00	0.05	0.01	0.31	0.29	0.00
-0.01	-0.04	-0.03	-0.01	0.04	-0.01	-0.03	-0.03	-0.01	0.04	-0.02	-0.04	-0.04	-0.01	0.03
-0.05	-0.04	-0.05	0.12	0.21	-0.05	-0.04	-0.04	0.11	0.21	-0.05	-0.04	-0.04	0.13	0.21
-0.02	-0.01	-0.01	0.26	0.64	-0.02	-0.01	-0.01	0.27	0.66	-0.02	-0.01	-0.01	0.26	0.62
-0.05	-0.04	-0.04	0.00	-0.02	-0.06	-0.03	-0.04	0.01	-0.02	-0.05	-0.03	-0.04	0.01	-0.01
0.02	-0.01	0.06	-0.04	-0.04	0.04	-0.01	0.07	-0.50	-0.81	0.04	-0.01	0.06	-0.49	-0.78
0.03	0.13	0.00	-0.02	-0.05	0.03	0.13	0.00	-0.79	-0.84	0.02	0.13	0.01	-0.78	-0.83
-0.03	-0.03	-0.02	-0.04	-0.04	-0.03	-0.03	-0.02	-0.68	-0.65	-0.03	-0.03	-0.02	-0.67	-0.66
-0.01	0.02	-0.02	-0.06	-0.05	-0.02	0.01	-0.02	-0.85	-0.87	-0.01	0.01	-0.02	-0.84	-0.89

APPENDIX III - MC-PIECES, EDGE-SEALED (1/3)

GRADA

		0 RH 50%	2	4	6	8	10	13	15	16	17	20	22	24	27	29	31	34
	MASS (g)	initial mass (g)							1 day at RH80%									
	Specimen	28.6.	30.6.	2.7.	4.7.	6.7.	8.7.	11.7.	13.7.	14.7.	15.7.	18.7.	20.7.	22.7.	25.7.	27.7.	29.7.	1.8.
GRADA	D 1	90.60	90.64	90.67	90.67	90.73	90.72	90.77	91.50	91.65	91.73	91.97	92.11	92.23	92.40	92.56	92.66	92.78
	D 2	86.72	86.76	86.79	86.82	86.86	86.84	86.88	87.65	87.72	87.85	88.12	88.28	88.38	88.58	88.69	88.84	88.97
	D 3	89.69	89.72	89.74	89.78	89.82	89.81	89.88	90.57	90.68	90.79	91.06	91.16	91.33	91.58	91.73	91.83	92.00
	D 4	111.00	111.02	111.07	111.09	111.12	111.11	111.11	111.99	112.11	112.22	112.45	112.62	112.79	113.03	113.21	113.35	113.50
	D 5	81.54	81.56	81.60	81.64	81.66	81.63	81.70	82.44	82.58	82.71	83.02	83.2	83.34	83.56	83.74	83.84	83.96
	D 6	109.76	109.81	109.85	109.89	109.90	109.93	110.01	111.00	111.14	111.26	111.59	111.79	111.96	112.18	112.43	112.59	112.78
	D 7	91.00	91.04	91.06	91.12	91.13	91.14	91.19	91.92	92.06	92.13	92.40	92.51	92.67	92.88	93.04	93.16	93.33
	D 8	91.38	91.42	91.47	91.50	91.50	91.58	91.59	92.36	92.52	92.60	92.85	93.06	93.17	93.38	93.53	93.65	93.81
	D 9	101.39	101.48	101.53	101.57	101.60	101.58	101.66	102.36	102.65	102.79	103.15	103.28	103.56	103.85	104.09	104.24	104.45
	D 10	99.26	99.35	99.40	99.43	99.48	99.47	99.54	100.41	100.60	100.77	101.14	101.38	101.56	101.83	102.07	102.21	102.40
	D 11	91.87	91.92	91.92	91.95	91.96	91.99	92.03	92.72	92.89	92.95	93.19	93.29	93.36	93.53	93.64	93.75	93.85
	D 12	93.75	93.79	93.80	93.82	93.85	93.80	93.90	94.60	94.74	94.81	95.00	95.18	95.22	95.35	95.49	95.58	95.69
	D 13	92.92	92.97	92.99	93.00	93.03	93.00	93.09	93.84	93.96	94.07	94.26	94.43	94.52	94.71	94.83	94.92	95.00
	D 14	95.91	95.96	95.99	96.01	96.04	96.02	96.06	96.86	96.96	97.07	97.31	97.41	97.60	97.76	97.94	98.04	98.19
	D 15	95.68	95.74	95.79	95.81	95.85	95.83	95.90	96.71	96.81	96.96	97.25	97.46	97.62	97.87	98.10	98.22	98.39

36	37	38	41	43	45	48	50	52	55	56	57	58	59	62	64	66	69	70	73	76	78	
1 day at RH80%										few hours at RH50%												
3.8.	4.8.	5.8.	8.8.	10.8.	12.8.	15.8.	17.8.	19.8.	22.8.	23.8.	24.8.	25.8.	26.8.	29.8.	31.8.	2.9.	5.9.	6.9.	9.9.	12.9.	14.9.	WEIGHT (12
92.08	91.92	91.92	91.80	91.71	91.59	91.53	91.50	91.44	91.37	91.41	91.55	91.55	91.59	91.60	91.64	91.63	91.67	91.67	91.68	91.71	91.71	85.833
88.31	88.18	88.13	88.00	87.90	87.78	87.66	87.64	87.60	87.50	87.56	87.68	87.66	87.72	87.74	87.79	87.78	87.80	87.83	87.83	87.86	87.87	82.028
91.28	91.15	91.15	90.97	90.89	90.79	90.67	90.65	90.60	90.49	90.55	90.68	90.67	90.68	90.72	90.78	90.78	90.79	90.80	90.79	90.83	90.80	84.776
112.68	112.57	112.55	112.41	112.30	112.21	112.10	112.06	112.01	111.94	111.99	112.12	112.11	112.16	112.18	112.22	112.23	112.25	112.28	112.28	112.31	112.32	105.041
83.30	83.16	83.09	82.92	82.80	82.67	82.55	82.52	82.47	82.37	82.40	82.51	82.54	82.58	82.61	82.65	82.64	82.67	82.70	82.69	82.71	82.73	77.149
111.87	111.75	111.69	111.52	111.36	111.21	111.11	111.06	110.97	110.89	110.95	111.07	111.10	111.12	111.18	111.24	111.24	111.26	111.29	111.28	111.30	111.31	104.024
92.56	92.48	92.43	92.34	92.22	92.12	92.02	92.00	91.86	91.87	91.91	92.01	92.03	92.07	92.09	92.14	92.14	92.16	92.18	92.17	92.19	92.18	86.244
93.13	92.98	92.93	92.80	92.69	92.58	92.46	92.41	92.30	92.26	92.31	92.41	92.45	92.46	92.51	92.57	92.57	92.58	92.61	92.59	92.62	92.61	86.586
103.63	103.50	103.40	103.17	103.00	102.89	102.73	102.68	102.61	102.49	102.54	102.66	102.71	102.75	102.80	102.85	102.84	102.89	102.92	102.92	102.95	102.96	96.004
101.54	101.32	101.27	101.06	100.90	100.75	100.63	100.59	100.51	100.42	100.48	100.60	100.64	100.70	100.74	100.79	100.80	100.84	100.86	100.87	100.89	100.90	94.196
93.18	93.07	93.04	92.97	92.88	92.77	92.71	92.72	92.61	92.60	92.64	92.74	92.75	92.80	92.80	92.87	92.85	92.86	92.89	92.87	92.91	92.89	87.079
95.01	94.91	94.91	94.84	94.77	94.66	94.61	94.55	94.50	94.46	94.53	94.64	94.65	94.68	94.70	94.74	94.73	94.75	94.76	94.76	94.78	94.77	88.772
94.30	94.20	94.15	94.06	93.99	93.90	93.82	93.79	93.70	93.70	93.75	93.86	93.87	93.90	93.92	93.97	93.97	93.98	93.99	93.97	94.00	93.98	87.878
97.41	97.33	97.28	97.12	97.05	96.97	96.88	96.88	96.83	96.76	96.81	96.95	96.95	96.99	97.00	97.04	97.02	97.05	97.07	97.08	97.10	97.11	90.784
97.61	97.45	97.39	97.21	97.08	96.97	96.85	96.81	96.76	96.66	96.72	96.84	96.87	96.92	96.93	96.99	96.97	97.02	97.01	97.03	97.05	97.06	90.633

G – Grada
PW – conventional plywood

FG – formed Grada
UFG – unsanded formed Grada
FB – formed beech

APPENDIX III - MC-PIECES, EDGE-SEALED (2/3)

CONVENTIONAL PLYWOOD

MASS (g)		initial mass (g)							1 day at RH80%									
	Specimen	28.6.	30.6.	2.7.	4.7.	6.7.	8.7.	11.7.	13.7.	14.7.	15.7.	18.7.	20.7.	22.7.	25.7.	27.7.	29.7.	1.8.
PW	D 1	85.57	85.63	85.67	85.71	85.73	85.78	85.82	86.60	86.91	87.14	87.73	88.02	88.24	88.47	88.68	88.81	88.98
	D 2	90.46	90.51	90.57	90.62	90.68	90.66	90.74	91.56	91.91	92.19	92.78	93.08	93.31	93.62	93.79	93.89	94.01
	D 3	85.75	85.84	85.90	85.96	85.97	85.95	86.06	86.77	87.06	87.28	87.80	88.15	88.32	88.54	88.82	88.93	89.07
	D 4	110.13	110.27	110.31	110.39	110.45	110.47	110.54	111.54	111.88	112.15	112.88	113.27	113.55	113.80	114.04	114.22	114.34
	D 5	109.77	109.87	109.93	109.97	110.03	110.06	110.12	111.20	111.46	111.70	112.35	112.75	112.96	113.38	113.66	113.84	114.12
	D 6	108.41	108.55	108.59	108.66	108.87	108.69	108.78	109.78	110.08	110.30	110.90	111.39	111.65	112.04	112.34	112.54	112.83
	D 7	86.45	86.67	86.69	86.76	86.80	86.79	86.87	87.70	87.92	88.14	88.69	88.99	89.26	89.57	89.85	89.96	90.13
	D 8	100.55	100.68	100.74	100.81	100.86	100.88	100.96	101.86	102.12	102.38	103.05	103.44	103.70	104.60	104.36	104.55	104.73
	D 9	95.96	96.06	96.10	96.16	96.18	96.20	96.27	97.20	97.46	97.67	98.31	98.61	98.84	99.10	99.36	99.49	99.66
	D 10	85.25	85.32	85.34	85.36	85.42	85.41	85.48	86.21	86.41	86.57	87.06	87.33	87.55	87.87	88.10	88.28	88.47
	D 11	92.35	92.44	92.50	92.56	92.60	92.60	92.64	93.52	93.77	94.00	94.58	94.89	95.14	95.53	95.81	96.00	96.12
	D 12	100.43	100.50	100.58	100.63	100.67	100.63	100.75	101.69	101.93	102.14	102.71	103.05	103.31	103.70	104.00	104.19	104.36
	D 13	100.50	100.56	100.61	100.63	100.69	100.65	100.74	101.64	101.93	102.12	102.61	102.83	103.21	103.60	103.85	104.02	104.24
	D 14	106.66	106.75	106.87	106.93	106.99	106.97	107.09	108.09	108.38	108.74	109.45	109.76	110.10	110.52	110.86	111.01	111.19
	D 15	104.52	104.61	104.64	104.69	104.75	104.72	104.76	105.81	106.10	106.32	106.84	107.11	107.43	107.88	108.20	108.42	108.66

MASS (g)		1 day at RH80%										few hours at RH50%												
	Specimen	3.8.	4.8.	5.8.	8.8.	10.8.	12.8.	15.8.	17.8.	19.80	22.8.	23.8.	24.8.	25.8.	26.8.	29.8.	31.8.	2.9.	5.9.	6.9.	9.9.	12.9.	14.9.	WEIGHT (2
PW	D 1	87.90	87.51	87.24	86.71	86.40	86.16	85.89	85.77	85.63	85.50	85.54	85.72	85.79	85.87	85.99	86.08	86.11	86.15	86.19	86.20	86.23	86.21	79.091
	D 2	92.82	92.40	92.10	91.54	91.19	90.91	90.67	90.57	90.41	90.30	90.28	90.52	90.61	90.70	90.85	90.96	91.00	91.04	91.09	91.08	91.15	91.14	83.802
	D 3	88.06	87.66	87.41	86.86	86.57	86.34	86.09	85.95	85.84	85.74	85.76	85.92	86.02	86.07	86.13	86.29	86.32	86.35	86.39	86.40	86.43	86.43	79.433
	D 4	113.05	112.57	112.23	111.57	111.19	110.91	110.58	110.45	110.25	110.11	110.16	110.36	110.46	110.54	110.72	110.85	110.88	110.92	110.97	110.97	111.02	111.02	102.052
	D 5	112.75	112.30	112.05	111.52	111.21	110.91	110.67	110.55	110.39	110.24	110.31	110.51	110.57	110.66	110.78	110.87	110.90	110.93	110.99	110.97	111.03	111.01	102.273
	D 6	111.48	111.11	110.85	110.37	110.03	109.81	109.55	109.46	109.26	109.13	109.16	109.38	109.47	109.53	109.65	109.73	109.74	109.78	109.82	109.81	109.86	109.85	101.037
	D 7	89.11	88.73	88.48	87.97	87.65	87.40	87.15	87.03	86.87	86.79	86.78	86.96	87.00	87.09	87.22	87.31	87.33	87.36	87.41	87.42	87.45	87.43	80.196
	D 8	103.51	103.04	102.79	102.15	101.82	101.55	101.23	101.11	101.00	100.81	100.84	101.05	101.14	101.22	101.35	101.43	101.46	101.54	101.57	101.59	101.63	101.65	93.274
	D 9	98.52	98.06	97.76	97.15	96.78	96.55	96.28	96.12	95.98	95.86	95.80	96.09	96.18	96.27	96.40	96.54	96.57	96.62	96.65	96.66	96.70	96.69	88.867
	D 10	87.46	87.11	86.88	86.38	86.09	85.87	85.62	85.52	85.42	85.27	85.31	85.49	85.56	85.63	85.72	85.80	85.83	85.90	85.91	85.94	85.97	85.98	79.083
	D 11	94.93	94.51	94.23	93.62	93.29	93.03	92.74	92.64	92.51	92.35	92.39	92.62	92.69	92.77	92.90	93.00	93.02	93.10	93.12	93.15	93.20	93.21	85.565
	D 12	103.12	102.74	102.52	101.99	101.67	101.42	101.15	101.03	100.92	100.75	100.82	100.98	101.06	101.15	101.25	101.33	101.35	101.41	101.43	101.46	101.49	101.51	93.438
	D 13	103.03	102.66	102.39	101.83	101.54	101.28	100.98	100.87	100.70	100.58	100.59	100.78	100.83	100.92	101.06	101.15	101.19	101.23	101.27	101.27	101.30	101.28	93.271
	D 14	109.75	109.23	108.87	108.09	107.71	107.42	107.04	106.91	106.79	106.61	106.64	106.90	106.99	107.12	107.29	107.43	107.46	107.54	107.59	107.62	107.67	107.69	98.841
	D 15	107.42	107.05	106.80	106.25	105.95	105.71	105.40	105.29	105.15	104.99	105.00	105.22	105.29	105.36	105.47	105.54	105.56	105.62	105.64	105.67	105.70	105.72	97.377

APPENDIX III - MC-PIECES, EDGE-SEALED (3/3)

FORMED SPECIMENS (FG, UFG AND FB)

		initial mass (g)							1 day at RH80%									
	specimen	28.6.	30.6.	2.7.	4.7.	6.7.	8.7.	11.7.	13.7.	14.7.	15.7.	18.7.	20.7.	22.7.	25.7.	27.7.	29.7.	1.8.
FG	FGM1	336.75	336.92	337.06	337.16	337.27	337.36	337.4	337.90	341.27	341.85	342.57	343.18	343.83	344.58	345.07	345.48	346.34
	FGM2	332.23	332.43	332.56	332.7	332.86	332.95	333.03	336.42	336.70	337.27	338.59	336.64	339.99	340.72	341.50	342.13	342.66
	FGM3	336.02	336.27	336.34	336.47	336.59	336.63	336.84	340.78	340.90	341.63	342.64	343.56	343.88	344.64	345.31	345.77	346.35
	FGM4	336.74	336.98	337.08	337.15	337.29	337.27	337.38	340.69	341.21	341.58	342.43	343.15	344.02	344.39	345.01	345.51	346.07
UFG	UFGM1	377.8	378.1	378.37	378.53	378.71	378.72	379.01	383.79	385.16	385.95	387.87	389.12	390.21	391.47	392.98	393.76	394.67
	UFGM2	361.7	362	362.13	362.31	362.41	362.42	362.55	367.03	367.70	368.63	370.15	371.36	372.34	373.52	374.53	375.89	376.72
	UFGM3	358.3	358.61	358.76	358.98	359.1	359.04	359.29	363.70	364.50	365.36	367.07	368.26	369.33	370.6	372.02	372.55	373.59
	UFGM4	363.44	363.83	363.92	364.05	364.19	364.16	364.34	368.71	369.43	370.18	371.62	372.6	373.42	374.58	375.42	376.18	377.11
beech	FB1	388.3	388.86	389.15	389.31	390.4	389.38	389.6	395.49	397.63	399.41	402.40	403.98	405.08	406.23	406.85	407.29	408.06
	FB2	381.8	382.37	382.56	382.72	382.79	382.7	382.73	389.50	391.19	392.88	395.61	396.99	397.89	398.57	399.33	399.79	400.13

G – Grada
PW – conventional plywood

1 day at RH80%																						DRY WEIGHT
3.8.	4.8.	5.8.	8.8.	10.8.	12.8.	15.8.	17.8.	19.80	22.8.	23.8.	24.8.	25.8.	26.8.	29.8.	31.8.	2.9.	5.9.	6.9.	9.9.	12.9.	14.9.	
342.97	342.72	342.54	342.13	341.84	341.66	341.38	341.19	341.05	340.84	341.11	341.51	341.55	341.80	341.76	341.91	341.93	342.05	342.11	342.18	342.27	342.28	321.361
339.29	338.84	338.69	338.21	337.86	337.62	337.29	337.02	336.85	336.61	337.86	338.07	337.97	337.98	338.12	338.21	338.21	338.28	338.36	338.43	338.46	338.49	317.155
343.11	342.72	342.53	341.99	341.58	341.36	341.01	340.78	340.64	340.30	340.63	341.00	341.11	341.22	341.37	341.52	341.53	341.67	341.72	341.74	341.84	341.86	320.184
342.86	342.43	342.34	341.91	341.61	341.41	341.12	340.90	340.80	340.56	340.84	341.30	341.38	341.48	341.62	341.74	341.74	341.87	341.93	341.99	342.06	342.06	321.105
389.64	388.75	388.28	387.07	386.33	385.86	385.18	384.75	384.46	383.94	384.27	385.00	385.48	385.43	385.66	385.81	385.83	385.99	386.06	386.14	386.19	386.21	359.644
372.23	371.51	371.13	370.19	369.62	369.21	368.62	368.26	367.98	367.53	367.92	368.64	368.74	368.81	369.05	369.68	369.84	369.63	369.73	369.75	369.77	369.77	344.353
369.05	368.26	367.86	366.86	366.17	365.72	365.14	364.73	364.42	363.95	364.32	365.08	365.18	365.28	365.42	365.54	365.59	365.69	365.77	365.82	365.86	365.89	340.491
372.62	372.03	371.64	370.88	370.36	370.02	369.48	369.19	368.96	368.63	368.80	369.57	369.68	369.85	370.00	370.13	370.14	370.27	370.33	370.38	370.46	370.49	345.863
399.19	395.33	392.90	388.77	387.20	386.54	385.78	385.42	385.28	385.05	385.69	387.57	388.92	389.61	390.80	391.12	391.25	391.40	391.53	391.57	391.59	391.58	358.208
391.87	388.03	385.72	381.83	380.38	379.71	379.07	378.74	378.65	378.38	379.03	381.02	382.35	383.01	384.15	384.42	384.64	384.70	384.84	384.86	384.85	384.92	352.172

FG – formed Grada
UFG – unsanded formed Grada
FB – formed beech

APPENDIX IV – MC-PIECES, DELAMINATION OF THE UNSANDED FORMED GRADA (UFG)

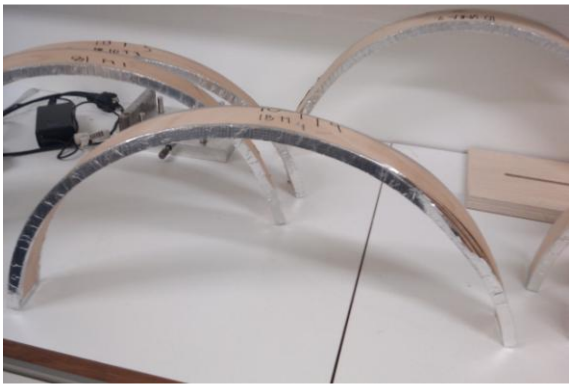


Figure 60 UFG M 4

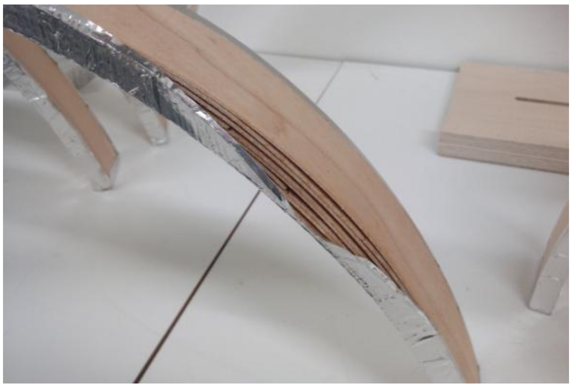


Figure 61 UFG M 2

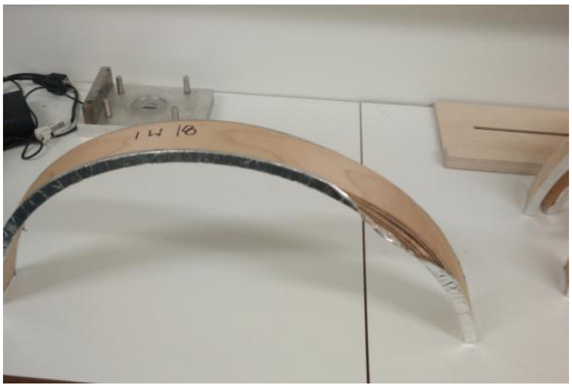


Figure 62 UFG M 1

APPENDIX V – MC-PIECES, SURFACE SEALED (1/3)

ALL FOUR EDGES OPEN

RH 80%
T 20C

Square plates. Surfaces are sealed with aluminium tape. Specimen have different side lenghts (50, 100 and 150mm)

MASS (g)		2.8.	3.8.	4.8.	5.8.	8.8.	10.8.	11.8.	12.8.	15.8.	17.8.	19.8.	22.8.	23.8.	24.8.	25.8.	26.8.	29.8	31.8.	2.9	5.9.	6.9.	9.9.	12.9.	14.9.
edges 50mm	G_N 5_1	25.23	25.78	26.00	26.14	26.32	26.33	26.37	26.38	26.45	26.42	26.43	26.42	26.44	26.45	26.44	26.49	26.42	26.48	26.46	26.47	26.49	26.46	26.49	26.49
	G_N 5_2	25.23	25.79	26.01	26.15	26.29	26.36	26.35	26.37	26.44	26.41	26.43	26.41	26.41	26.40	26.44	26.50	26.45	26.50	26.47	26.50	26.51	26.45	26.52	26.54
	PW_N 5_1	26.93	27.42	27.55	27.63	27.68	27.73	27.75	27.73	27.81	27.78	27.78	27.78	27.79	27.82	27.78	27.83	27.83	27.84	27.81	27.88	27.87	27.83	27.86	27.86
	PW_N 5_2	26.76	27.25	27.38	27.45	27.50	27.52	27.55	27.53	27.61	27.61	27.56	27.57	27.59	27.60	27.58	27.62	27.63	27.65	27.61	27.66	27.64	27.63	27.68	27.68
edges 100mm	G_N 10_1	100.42	101.63	102.24	102.70	103.62	104.13	104.36	104.49	104.93	105.08	105.22	105.41	105.46	105.53	105.53	105.57	105.71	105.86	105.90	105.79	105.95	105.93	105.96	106.03
	G_N 10_2	100.66	101.92	102.50	103.02	103.96	104.44	104.61	104.71	105.11	105.30	105.43	105.66	105.71	105.76	105.74	105.81	105.88	106.03	106.03	106.13	106.14	106.13	106.18	106.25
	PW_N 10_1	107.92	109.02	109.46	109.72	110.29	110.55	110.58	110.63	110.91	110.92	110.99	111.00	111.05	111.15	111.15	111.24	111.34	111.32	111.32	111.43	111.39	111.42	111.48	111.54
	PW_N 10_2	106.45	107.50	107.98	108.25	108.71	108.91	109.01	109.02	109.22	109.27	109.31	109.40	109.40	109.46	109.49	109.49	109.48	109.61	109.57	109.55	109.64	109.59	109.65	109.63
	G_N 15_1	222.72	224.30	225.16	225.91	227.41	228.15	228.49	228.67	229.72	230.15	230.55	231.19	231.33	231.48	231.56	231.68	232.00	232.20	232.34	232.61	232.78	232.87	233.18	233.21
edges 150mm	G_N 15_2	227.92	229.69	230.57	231.08	232.48	233.28	233.65	233.88	234.72	235.13	235.56	236.20	236.31	236.54	236.72	236.86	237.29	237.43	237.60	237.82	237.92	238.22	238.33	238.59
	PW_N 15_1	247.98	249.70	250.45	250.80	251.74	252.29	252.45	252.62	253.10	253.19	253.52	253.87	253.87	253.44	254.00	254.06	254.22	254.47	254.58	254.75	254.75	254.94	254.80	254.92
	PW_N 15_2	239.25	240.76	241.44	241.94	242.89	243.48	243.70	243.75	244.42	244.63	244.88	245.06	245.21	245.32	245.32	245.37	245.56	245.66	245.74	245.89	245.91	245.91	246.22	246.36

G – Grada
PW – conventional plywood

FG – formed Grada
UFG – unsanded formed Grada
FB – formed beech

APPENDIX V – MC-PIECES, SURFACE SEALED (2/3)

ALL FOUR EDGES OPEN

Sealed&urfaces&&dge&0mm

Conditions&efore&rying
RH#80%
T#20C

**Test&pecimen&with&ealed&urfaces)&were&
cut&nto&maller&pieces&and&hese&pieces'&
moisture&ontent&was&measured.**

		Moisture&ontent		
	G 5_1	11.5	11.6	11.4
av	**11.6**	11.8	11.7	11.5
st.dev	**0.018**	11.6	11.6	11.7

	G 5_2	11.0	11.3	11.2
av	**11.3**	11.3	11.5	11.2
st.dev	**0.020**	11.4	11.4	11.2

	PW 5_1	11.4	11.5	11.5
av	**11.3**	11.6	11.4	11.3
st.dev	**0.022**	11.1	11.2	11.2

	PW 5_2	11.4	11.3	11.4
av	**11.4**	11.4	11.4	11.4
st.dev	**0.007**	11.3	11.2	11.4

Sealed&urfaces&&dge&00mm

Conditions&efore&rying
RH#80%
T#20C

**Test&pecimen&with&ealed&urfaces)&were&
cut&nto&maller&pieces&and&hese&pieces'&
moisture&ontent&was&measured.**

	Moisture&ontent			
G 10_1	11.8	11.7	11.7	11.6
11.5	11.5	11.3	11.3	11.1
0.039	11.7	11.6	11.3	11.3
	11.6	11.5	11.4	11.3

G 10_2	11.4	11.7	11.5	11.4
11.5	11.8	11.6	11.4	11.4
0.015	11.6	11.5	11.3	11.3
	11.4	11.5	11.4	11.4

PW 10_1	11.5	11.4	11.6	11.5
11.4	11.5	11.2	11.4	11.4
0.011	11.5	11.3	11.2	11.3
	11.4	11.3	11.4	11.3

PW 10_2	11.7	11.6	11.4	11.4
11.4	11.5	11.6	11.5	11.4
0.013	11.5	11.5	11.5	11.3
	11.5	11.4	11.3	11.2

Sealed&urfaces&&dge&50mm

Conditions&efore&rying
RH#80%
T#20C

**Test&pecimen&with&ealed&urfaces)&were&
cut&nto&maller&pieces&and&hese&pieces'&
moisture&ontent&was&measured.**

	Moisture&ontent			
G 15_1	11.4	11.0	10.9	11.1
	11.2	10.8	10.8	11.1
11.0	11.2	10.8	10.7	11.0
0.033	11.3	11.1	11.0	11.0

G 15_2	11.2	11.0	10.9	11.1
	11.2	10.8	10.7	11.1
11.0	11.2	10.7	10.7	11.1
0.038	11.3	11.1	11.0	11.1

PW 15_1	11.3	11.3	11.2	11.3
	11.3	11.1	11.1	11.2
11.2	11.3	11.1	11.2	11.2
0.008	11.3	11.2	11.2	11.3

PW 15_2	11.3	11.3	11.2	11.3
	11.2	10.9	11.0	11.2
11.2	11.2	11.0	11.1	11.2
0.012	11.3	11.2	11.1	11.3

APPENDIX V – MC-PIECES, SURFACE SEALED (3/3)

ONLY ONE EDGE OPEN G AND PW (LEFT), SPECIAL MADE MATERIAL (MIDDLE AND RIGHT)

MASS (g) \ date	2.8.	3.8.	4.8.	5.8.	8.8	10.8.	12.8.	15.8.	17.8.	19.8.	22.8.	23.8.	24.8.	25.8.
S_T 1	147.26	147.39	147.49	147.55	147.75	147.97	148.08	148.30	148.42	148.53	148.68	148.75	148.84	148.90
S_T 2	147.39	147.55	147.68	147.79	148.06	148.23	148.38	148.65	148.77	148.90	149.08	149.14	149.26	149.25
$S_{=}$ 1	147.20	147.56	147.78	147.92	148.31	148.52	148.69	149.00	149.13	149.28	149.46	149.52	149.64	149.65
$S_{=}$ 2	147.38	147.77	148.00	148.16	148.56	148.74	148.97	149.25	149.40	149.59	149.85	149.92	150.03	150.04

26.8.	29.8	31.8.	2.9	5.9.	6.9.	9.9.	12.9.	14.9.	Average	Difference btw the first and the last
148.95	149.07	149.18	149.25	149.44	149.46	149.59	149.75	149.85	**148.63**	2.59
149.37	149.53	149.68	149.77	149.92	150.03	150.17	150.36	150.47	**149.02**	3.08
149.74	149.92	150.03	150.11	150.33	150.41	150.52	150.69	150.79	**149.31**	3.59
150.14	150.34	150.46	150.55	150.75	150.81	151.00	151.19	151.32	**149.66**	3.94

Moisture penetration

Conditions before drying
RH 80%
T 20C

formable plywood (P) and conventional plywood (UF). Only one edge is unsealed, both surfaces and rest of the edges

Moisture content

	G_1	G_2	PW_1	PW_2
open edge	9.52	9.47	10.55	10.62
2	7.38	7.32	9.61	9.74
3	6.54	6.75	9.14	9.29
4	6.21	6.77	8.96	9.00
5	6.34	7.24	8.81	8.85

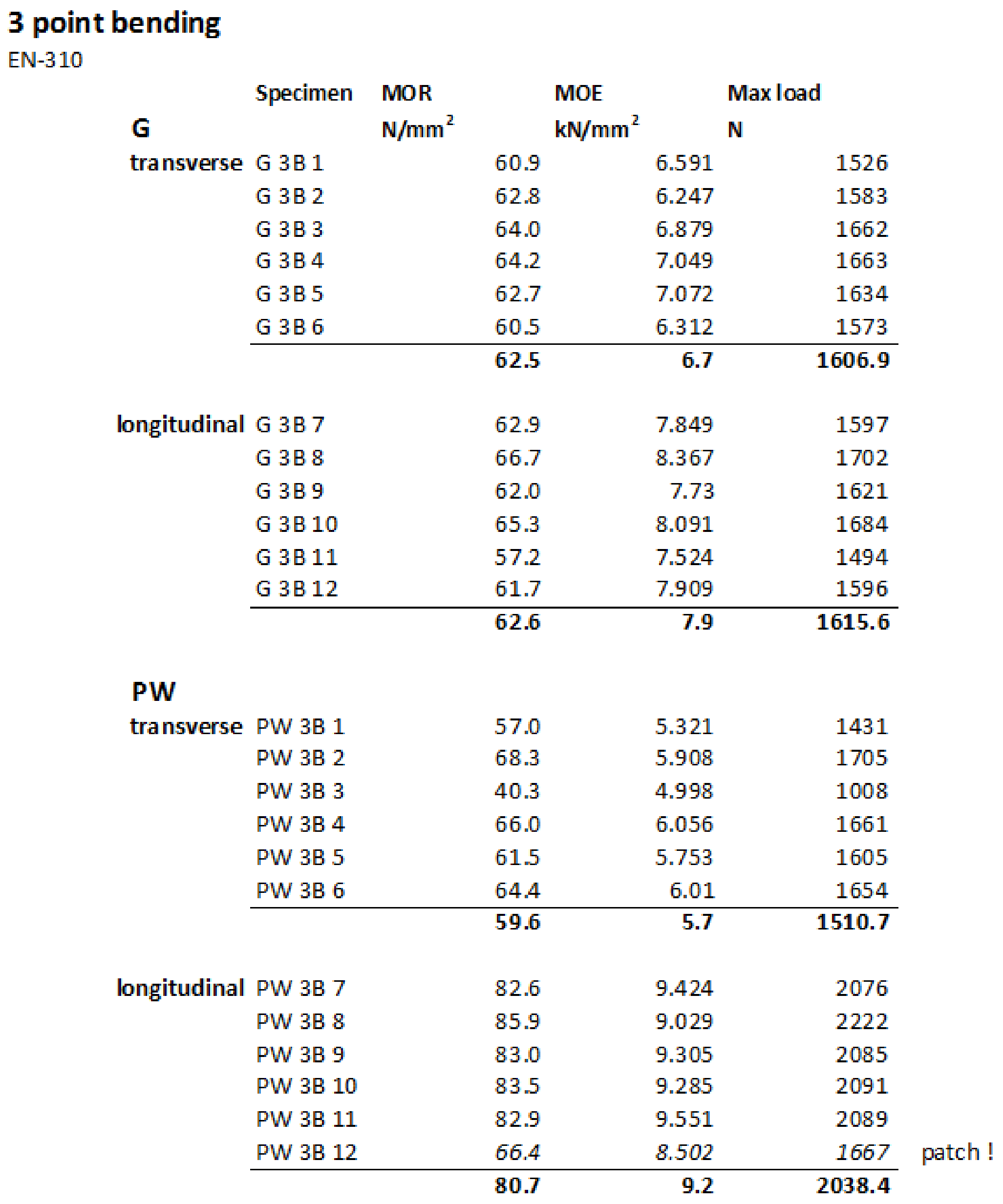
AVERAGE

G	PW
9.50	10.58
7.35	9.67
6.64	9.22
6.49	8.98
6.79	8.83

	Moisture content					
	open edge	2	3	4	AVERAGE	variance
S_T 1	8.58	7.91	8.45	7.75	**8.17**	0.045863
S_T 2	9.05	7.93	8.51	8.41	**8.48**	
S_T AV	**8.82**	**7.92**	**8.48**	**8.08**		
$S_{=}$ 1	10.48	8.95	7.94	7.60	**8.74**	
$S_{=}$ 2	10.53	8.87	8.07	7.85	**8.83**	0.003872
$S_{=}$ AV	**10.50**	**8.91**	**8.01**	**7.72**		

APPENDIX VI – STRENGTH TESTS (1/5)

BENDING TESTS



3 point bending

EN-310

	Specimen	MOR N/mm^2	MOE kN/mm^2	Max load N	
G					
transverse	G 3B 1	60.9	6.591	1526	
	G 3B 2	62.8	6.247	1583	
	G 3B 3	64.0	6.879	1662	
	G 3B 4	64.2	7.049	1663	
	G 3B 5	62.7	7.072	1634	
	G 3B 6	60.5	6.312	1573	
		62.5	**6.7**	**1606.9**	
longitudinal	G 3B 7	62.9	7.849	1597	
	G 3B 8	66.7	8.367	1702	
	G 3B 9	62.0	7.73	1621	
	G 3B 10	65.3	8.091	1684	
	G 3B 11	57.2	7.524	1494	
	G 3B 12	61.7	7.909	1596	
		62.6	**7.9**	**1615.6**	
PW					
transverse	PW 3B 1	57.0	5.321	1431	
	PW 3B 2	68.3	5.908	1705	
	PW 3B 3	40.3	4.998	1008	
	PW 3B 4	66.0	6.056	1661	
	PW 3B 5	61.5	5.753	1605	
	PW 3B 6	64.4	6.01	1654	
		59.6	**5.7**	**1510.7**	
longitudinal	PW 3B 7	82.6	9.424	2076	
	PW 3B 8	85.9	9.029	2222	
	PW 3B 9	83.0	9.305	2085	
	PW 3B 10	83.5	9.285	2091	
	PW 3B 11	82.9	9.551	2089	
	PW 3B 12	*66.4*	*8.502*	*1667*	patch !
		80.7	**9.2**	**2038.4**	

APPENDIX VI – STRENGTH TESTS (2/5)

4 point bending

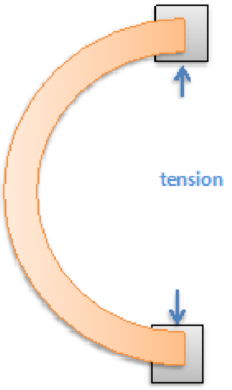
EN-408

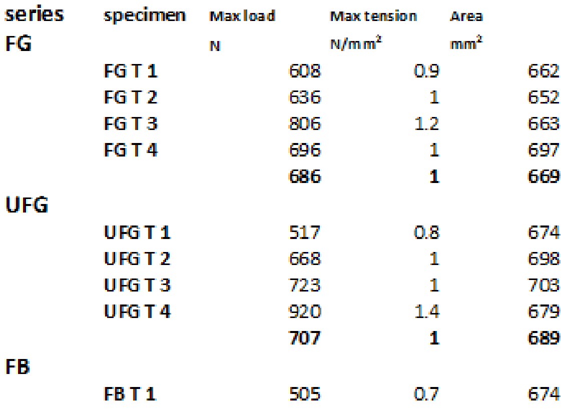
	Specimen	MOR	MOE	Max load
G		N/mm^2	kN/mm^2	N
transverse	G 4B 1	37.4	9.046	804
	G 4B 2	40.4	10.985	850
	G 4B 3	41	10.330	864
	G 4B 4	37.7	10.764	781
	G 4B 5	55.3	9.712	1144
	G 4B 6	59.3	10.434	1231
		45.2	**10.2**	**945.7**
longitudinal	G 4B 7	58.8	12.129	1219
	G 4B 8	56.9	11.953	1214
	G 4B 9	56.3	12.102	1185
	G 4B 10	56	12.167	1184
	G 4B 11	57.1	14.944	1209
	G 4B 12	57.9	12.021	1205
		57.2	**12.6**	**1202.6**
PW				
transverse	PW 4B 1	45.7	8.889	937
	PW 4B 2	40.3	9.284	835
	PW 4B 3	45.2	8.905	923
	PW 4B 4	43.8	8.649	915
	PW 4B 5	52.6	8.518	1087
	PW 4B 6	43.1	9.058	904
		45.1	**8.9**	**933.4**
longitudinal	PW 4B 7	52.9	12.445	1091
	PW 4B 8	74.7	13.552	1515
	PW 4B 9	81.3	13.634	1658
	PW 4B 10	66.3	13.281	1353
	PW 4B 11	76.5	12.982	1529
	PW 4B 12	77.2	13.493	1547
		71.5	**13.2**	**1448.8**

APPENDIX VI – STRENGTH TESTS (3/5)

TENSION AND COMPRESSION TESTS

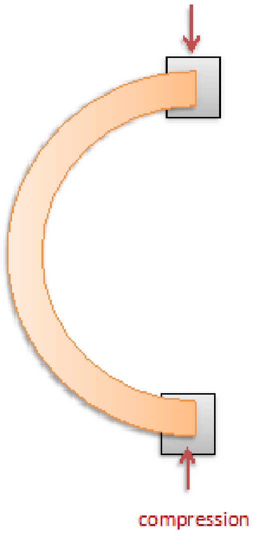
Tension

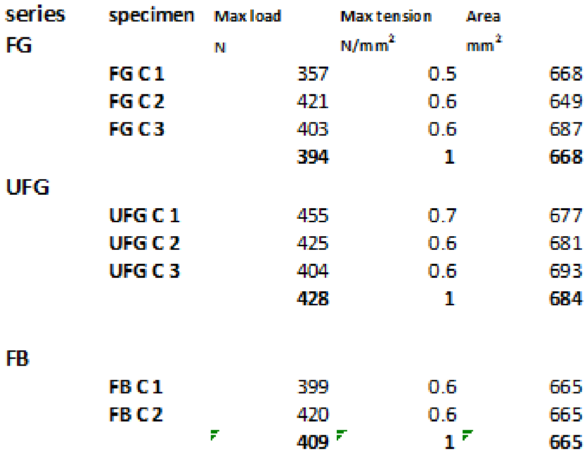




series	specimen	Max load N	Max tension N/mm²	Area mm²
FG				
	FG T 1	608	0.9	662
	FG T 2	636	1	652
	FG T 3	806	1.2	663
	FG T 4	696	1	697
		686	**1**	**669**
UFG				
	UFG T 1	517	0.8	674
	UFG T 2	668	1	698
	UFG T 3	723	1	703
	UFG T 4	920	1.4	679
		707	**1**	**689**
FB				
	FB T 1	505	0.7	674

Compression





series	specimen	Max load N	Max tension N/mm²	Area mm²
FG				
	FG C 1	357	0.5	668
	FG C 2	421	0.6	649
	FG C 3	403	0.6	687
		394	**1**	**668**
UFG				
	UFG C 1	455	0.7	677
	UFG C 2	425	0.6	681
	UFG C 3	404	0.6	693
		428	**1**	**684**
FB				
	FB C 1	399	0.6	665
	FB C 2	420	0.6	665
		409	**1**	**665**

APPENDIX VI – STRENGTH TESTS (4/5)

IMPACT TEST (GRADA)

Span 40mm

Sample	Direction	Test specime	thickness	width	cut area	mass	value	impact energy
Grada	=========	1	12.95	13.28	172	15.68	9	52
FORMED		2	12.94	13.36	173	15.738	10	58
FG		3	12.93	13.38	173	15.84	10	58
		4	12.89	13.38	172	16.105	15	87
		5	12.86	13.37	172	16.263	28	163
		6	12.8	13.33	171	15.993	9	53
		7	12.82	13.37	171	15.89	29	169
		8	12.82	13.39	172	16.341	11	64
		9	12.8	13.29	170	15.931	11	65
		10	12.75	13.27	169	15.9	9	53
		ca	**12.86**	**13.34**	**171.53**	**15.97**	**14.10**	**82.17**
		st.dev	***0***	***0***	***1***	***0***	***8***	***45***
Grada	▭	1	13.03	13.02	170	15.76	16	94
FORMED		2	13.37	13.04	174	16.06	14	80
FG		3	13.25	13.04	173	16.15	18	104
		4	13.31	13.04	174	16.17	14	81
		5	13.34	13.01	174	16.18	15	86
		6	13.37	12.99	174	16.11	33	190
		7	13.34	13.05	174	15.76	18	103
		8	13.16	13.05	172	15.99	17	99
		9	13.33	13.01	173	15.74	15	86
		10	13.39	12.94	173	15.66	11	63
		ca	**13.29**	**13.02**	**173.01**	**15.96**	**17.10**	**98.83**
		st.dev	***0***	***0***	***1***	***0***	***6***	***34***
Grada	=========	1	15.08	15.06	227	25.074	15	66
FORMABLE		2	15.07	15.04	227	24.693	13	57
		3	15.07	15.05	227	24.867	15	66
		4	15.04	14.99	225	24.396	14	62
		5	15.1	15.12	228	24.926	15	66
		6	15.12	14.99	227	25.274	14	62
		7	15.07	15.15	228	24.734	15	66
		8	15.11	15.08	228	25.039	14	61
		9	15.03	15.09	227	24.344	15	66
		10	15.08	15.08	227	24.481	14	62
		ca	**15.08**	**15.07**	**227.13**	**24.78**	**14.40**	**63.40**
		st.dev	***0***	***0***	***1***	***0***	***1***	***3***
Grada	▭	1	15.15	15.06	228	24.944	184	806
FORMABLE		2	15.04	15.05	226	24.695	178	786
		3	15.06	15.05	227	25.179	191	843
		4	14.94	15.07	225	24.303	135	600
		5	14.99	15.08	226	24.29	170	752
		6	14.96	15.08	226	24.936	163	723
		7	15.02	15.1	227	24.329	165	728
		8	15.04	15.07	227	24.72	124	547
		9	15.07	15.1	228	24.838	150	659
		10	15.02	15.06	226	24.755	170	752
		ca	**15.03**	**15.07**	**226.52**	**24.70**	**163.00**	**719.50**
		st.dev	***0***	***0***	***1***	***0***	***21***	***93***

APPENDIX VI – STRENGTH TESTS (5/5)

IMPACT TEST (CONVENTIONAL PLYWOOD)

	=========	1	14.8	14.76	218	25.52	52	238
PW FLAT		2	14.82	14.72	218	25.366	33	151
		3	14.8	14.95	221	25.71	177	800
		4	14.81	14.87	220	26.035	20	91
		5	14.81	14.97	222	25.682	22	99
		6	14.8	14.83	219	26.208	146	665
		7	14.8	14.93	221	25.828	23	104
		8	14.84	14.79	219	25.136	140	638
		9	14.83	14.82	220	25.007	33	150
		10	14.82	14.73	218	24.476	16	73
		ca	**14.81**	**14.84**	**219.78**	**25.50**	**66.20**	**300.99**
		st.dev	***0***	***0***	***1***	***1***	***62***	***283***

		1	14.81	14.8	219	25.275	138	630
PW FLAT		2	14.87	14.8	220	25.599	28	127
		3	14.98	14.81	222	25.777	93	419
		4	14.97	14.82	222	25.707	109	491
		5	14.96	14.83	222	25.852	44	198
		6	15	14.79	222	25.767	97	437
		7	14.87	14.81	220	25.491	28	127
		8	14.83	14.83	220	25.762	31	141
		9	14.87	14.81	220	25.861	90	409
		10	14.73	14.82	218	25.535	139	637
		ca	**14.89**	**14.81**	**220.54**	**25.66**	**79.70**	**361.64**
		st.dev	***0***	***0***	***1***	***0***	***44***	***200***