TALLINN UNIVERSITY OF TECHNOLOGY
SCHOOL OF ENGINEERING
Department of Materials and Environmental Technology

EFFECT OF VENEER THICKNESS AND SURFACE ROUGHNESS ON SHEAR BOND STRENGTH WITH DIFFERENT ADHESIVES

SPOONI PAKSUSE JA PINNAKAREDUSE MÕJU ERINEVATE LIIMIDEGA VALMISTATUD LIIMÜHENDUSE TUGEVUSELE

MASTER THESIS

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Tallinn 2021

AUTHOR'S DECLARATION

Hereby I declare, that I have written this thesis independently.
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24/05/2021

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THESIS TASK

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Thesis topic:
(in English) Effect of veneer thickness and surface roughness on shear bond strength with different adhesives
(in Estonian) Spooni paksuse ja pinnakareduse mõju erinevate liimidega valmistatud liimühenduse tugevusele

Thesis main objectives:

1. To evaluate the effects of different species on bond strength and analyse the significant differences in bond strength formed with different wood species.
2. To evaluate the effects of different veneer thicknesses on bond strength and analyse the significant differences in bond strength formed with different veneer thicknesses.
3. To assess the influences of different adhesives on bond strength and analyse the significant differences in bond strength formed with different adhesives.
4. To evaluate the effects of veneer surface roughness on bond strength and determine whether there is any correlation between surface roughness and bond strength or not.
5. To analyse the significant differences in surface roughness among wood species and veneer thicknesses to better understand the effect of surface roughness on bond strength.

Thesis tasks and time schedule:

No	Task description	Deadline
1.	Choosing the thesis topic	02.2020
2.	Writing literature overview	30.03.2021
3.	Experimental	16.04.2021
4.	Analysis and writing of theses	10.05.2021
5.	Pre-defence	14.05.2021
6.	Thesis submission date	24.05.2021
7.	Defence	02.06.2021

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LIST OF ABBREVIATIONS AND SYMBOLS

AS = Aspen

BA = Black Alder

BI = Birch

GA = Grey Alder

LPF = Lignin-Based Phenol-Formaldehyde

PF = Phenol formaldehyde

PU = Polyurethane

PVAc = Polyvinyl acetate

Ra = Arithmetical mean roughness value

Rq = Root Mean Square (RMS) Roughness

Rz = Average Maximum Height of the Profile

SR = Surface Roughness

PREFACE

The thesis work includes the manufacturing of veneers from logs of four different hardwood species, preparation of specimens, measuring the surface roughness profiles of specimens, identifying the ideal pressing conditions of different adhesives, adhesives mixing ratio, conditioning of samples, and finally evaluate the adhesive bond strength by conducting the lap shear test. These works and research aim to determine the effects of several factors like wood species, veneer thickness, veneer surface roughness, and different adhesives on bond strength. The thesis experiments were conducted in the Laboratory of Wood Technology, Department of Material and Environmental Technology of Tallinn University of Technology. The works were supervised closely by the supervisor Dr. Heikko Kallakas; Researcher, and Co-supervisor Dr. Anti Rohumaa, Researcher, Department of Materials and Environmental Technology, Tallinn University of Technology.

The author is highly thankful to his supervisor and Co-supervisor and appreciates the practical and constructive suggestions provided during the development of this work. Furthermore, the author would like to deliver special gratefulness to Dr. Christopher Glaab Hunt for his valuable suggestions and consultations. Moreover, the author also expressed his cordial gratitude towards the staff members of the Laboratory of Wood Technology.

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Keywords: Adhesive bond strength, Lap shear test, veneers thickness, veneer surface roughness, wood adhesives, master’s thesis.

1 INTRODUCTION

Adhesives are essential raw materials for woodworking technology. Adhesives found their applications in the process or production of various woodworking and wood-based composites and construction. Due to the enormous demand for adhesives by wood industries worldwide, the market share of adhesives reached USD 4.60 billion in 2018 and is estimated to grow approximately 4.7% from 2019 to 2025 (Grand View Research, 2019). However, the bonding technology of adhesives with wood is one of the key technologies for physically and mechanically stable products.

Bond formation of adhesives with wood is a complex mechanism and depends on several critical factors, such as the anatomical structure of wood, wettability of veneer surface, veneer thickness; degree of roughness, adhesive's quality, viscosity, and ranges of penetration into the wood cell wall. Furthermore, some processing parameters like curing temperature, applied pressure, adhesive spread, and moisture content are crucial factors that affect bonding.

In terms of wood veneer, the most significant factors influencing bond strength are veneer properties such as wettability, surface roughness. Lathe checks developed into the veneer due to the peeling process, and the depth of lathe checks increases and frequency decreases when the veneer thickness increases (Bekhta et al., 2020; Daoui et al., 2011) and ultimately reduce the bond strength. While, higher surface roughness can lead to the reduction of actual surface area (DeVallanc et al., 2007) and restriction of bond formation among the peaks only (Neese, 1997), formation of gaps in bond line leads to reduction of cohesive strength (Follrich et al., 2010), and so on. Thus, higher surface roughness can weaken the bond strength.

In terms of adhesive, crucial factors like adhesives reactivity, depth of penetration influence bond strength to a certain degree. The degree of penetration depends on the anatomical structure of wood (Ansell, 2015), roughness of specimen (Ferdosian et al., 2017), wettability of surface (Wei et al., 2012), the high viscosity of adhesive and certain filler (Veigel et al., 2011), and molecular weight of adhesive (Laborie et al., 2006). However, specific properties such as structural damage and surface cleanliness developed due to the machining processes can severely affect bond strength (Follrich et al., 2010).

Moreover, the lap shear strength test is a commonly used testing method to determine the resistance of a bonded joint against stresses and is considered one of the essential testing methods for woodworking technology to evaluate the bonding strength. Furthermore, bond strength evaluation is crucial to understand the bonding mechanism of adhesives with wood and the factors dominating the bond's performance.

Considering the importance of adhesive bond strength in the wood industry, this research aims to identify the significant factors affecting the bond strength evaluated by lap shear testing and their degree of influence. Thus, in this research, four hardwood species, black alder (*Alnus glutinosa*), grey alder (*Alnus incana*), European aspen (*Populus tremula*), and silver birch (*Betula pendula*), were used to produce veneer and polyvinyl acetate, polyurethane, phenol formaldehyde, and lignin-based phenol-formaldehyde adhesive were used for bonding, and single lap-shear strength test was conducted to evaluate the bond strength. The research objectives are:

1. To evaluate the effects of different species on bond strength and analyse the significant differences in bond strength formed with different wood species.
2. To evaluate the effects of different veneer thicknesses on bond strength and analyse the significant differences in bond strength formed with different veneer thicknesses.
3. To assess the influences of different adhesives on bond strength and analyse the significant differences in bond strength formed with different adhesives.
4. To evaluate the effects of veneer surface roughness on bond strength and determine whether there is any correlation between surface roughness and bond strength or not.
5. To analyse the significant differences in surface roughness among wood species and veneer thicknesses to better understand the effect of surface roughness on bond strength.

2 LITERATURE BACKGROUND

The literature background chapter consists of three different parts. The first part of the literature background introduces hardwood species used in this research and wood species properties and utilization. The second part presents a review of the effect of veneer thicknesses and surface roughness on adhesive bond strength evaluated by lap shear bond strength. The third part covers different adhesives and how they interact with varying species of wood.

2.1 Estonian Wood species and properties

2.1.1 Forest and Wood Industry in Estonia

Estonia is one of the most forested territories in the European Union and ranked fifth based on forest coverage in Europe with temperate mixed forest zone and temperate climates. Estonia's forests occupy approximately half of its landmass, almost 51.4% of its territory (Stat.ee, 2019). There are two main types of forest in Estonia, i.e., forest growing on mineral soil and swamp forest. The primary forest area of Estonia is located in north-eastern and central Estonia, which range from the north coast to the southern border.

Table 2.1.1. 1 Estonian forest coverage by landmass in 2020 (Food and Agriculture Organization of the United Nations, 2020).

FRA (Forest Area Resource) categories	Forest area (1000 ha)	Forest expansion (2015-2020)	Deforestation (2015-2020)	Forest area net change (2015-2020)
	2020	Area (1000 ha/year)	Area (1000 ha/year)	Area (1000 ha/year)
Naturally regenerating forest (a)	2222.66	8.49	5.01	3.48
Planted forest (b)	215.74			
Total Wooden Land, (a) + (b)	2438.40			
Total land area (c)	4347.00			

However, the forests in Estonia are notable for their diversity of trees with the characteristics of Scandinavian forests. There are three main dominant species, and they are Scots pine (*Pinus sylvestris*), Norway spruce (*Picea abies*), and silver birch (*Betula pendula*). Besides that, there are some other species and few alien tree species in the Estonian forest (Figure 2.1.1. 1) (Keskkonnaagentuur, 2018). However, the growing stock is also dominated by these three dominant species. Moreover, the three dominant species, Scots pine, Norway spruce, and silver birch, contributed almost 79% of the total growing stock of Estonia, which was 494.15 million dense meters in 2020. (Table 2.1.1. 2) (Food and Agriculture Organization of the United Nations, 2020).

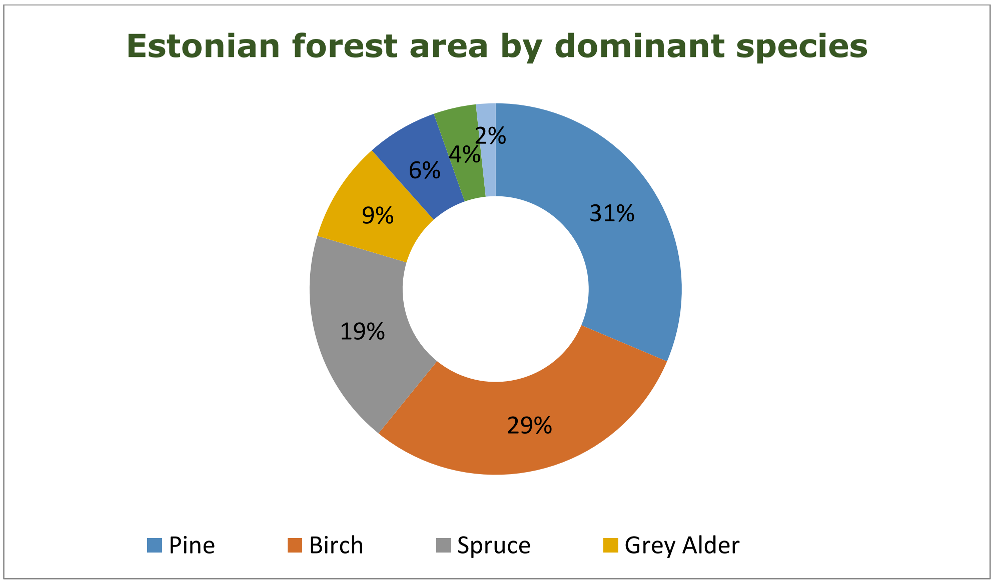


Figure 2.1.1. 1 Estonian forest area by dominant species (Keskkonnaagentuur, 2018).

Table 2.1.1. 2 Growing stock in 2020 by Species in terms of volume (Food and Agriculture Organization of the United Nations, 2020)

	Tree species	Growing stock in forest (million m^3 over bark)	
		2015	2020
Native tree species	Scots pine	158.22	150.95
	Silver birch, Downy birch	126.48	127.26
	Norway spruce	110.31	112.07
	Grey alder	34.3	32.93
	European aspen	31.51	32.91
	European alder	21.98	22.37
	European ash	4.04	4.07
	Willow species	3.21	3.27
	Common oak	2.55	2.89
	Bird cherry	0.82	0.91
Introduced tree species	Larch species	0.31	0.24
	Poplar (excluding aspen)	0.11	0.13
Total growing stock		491.78	494.15

The timber industry is one of the largest sectors of Estonia and has a remarkable contribution to the foreign trade of Estonia. The timber and wood industry in Estonia has over 1,100 companies and 17,000 workers and contributes almost 17% of the total Estonian trade export. Besides producing a wide range of products, this industry contributes to the production of wood-based energy. Almost 24% of the energy produced in Estonia is wood-based, which makes wood is one of the most valuable raw materials in Estonia (Keskkonnaagentuur, 2018). Moreover, this industry shows stable growth in the last few years.

However, another major industry with a long tradition and contribution to the economy of Estonia and depends on its forest industry for raw materials is Paper Industry. Estonian paper industry has almost 60 companies and approximately 1,400 workers. The typical products manufactured by the paper industry are paper, pulp, or paper products; among them, over 80% have been exported. In contrast, approximately 500 companies are operating in rural areas in Estonia and manufacturing furniture. Over 80% of these companies are micro-enterprises, and approximately 7,500 people are working in the furniture industry of Estonia.

Furthermore, more than 8,000 companies are operating in the construction industry in Estonia, and 90% of them are micro-enterprises (United Nations Economic Commission for Europe, 2014). Furthermore, these sectors contribute to the local economy of Estonia and have a significant effect on revenue generation. Figure 2.1.1. 2 illustrates the revenue distribution of wood and wooden articles exported by Estonia in 2019 (Keskkonnaagentuur, 2018).

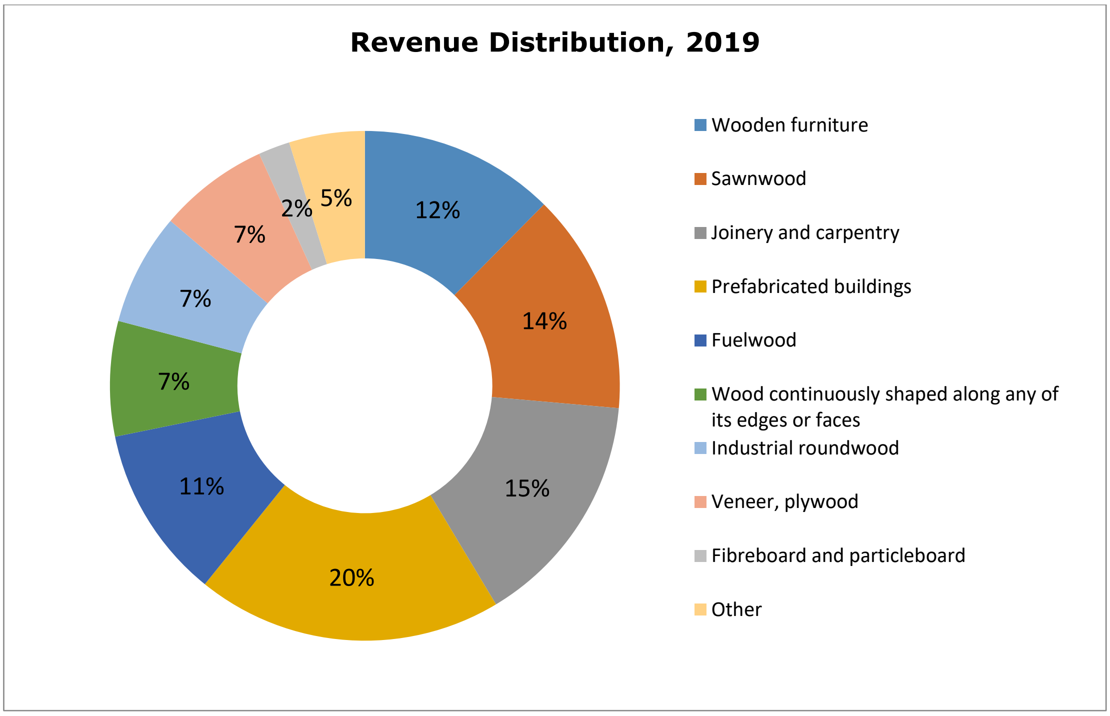


Figure 2.1.1. 2 Revenue distribution of wood and wooden articles exported by Estonia in 2019 (Keskkonnaagentuur, 2018).

2.1.2 Wood Species and their properties

Wood is produced by the living organism known as a tree and has fibrous, heterogeneous, and anisotropic texture. However, wood is also defined as the secondary xylem of trees often (Hickey and King, 2001). In general, wood has been classified into two groups, such as Softwood and Hardwood. Softwood comes from coniferous trees, also known as evergreen trees, and Hardwood comes from deciduous trees. There are several Hardwood and softwood species available in Estonia. However, the properties of four different hardwood species will be discussed as they were used in this research.

Silver birch (*Betula pendula*)

Birch belongs to the family *Betulaceae* and genus *Betula* and native to Europe and parts of Asia, also grows profusely in North America. The bark of Birch is white and smooth, though it darkens and becomes irregular when it grows older. Birch sapwood tends to be nearly white, and the heartwood is golden brown. Wood grain is straight or slightly wavy with fine and even texture. It does not have any characteristic odor. However, Birch tends to rot and decay when exposed and vulnerable to insect attack (Maier, 2008).

Moreover, Birch is diffuse-porous with medium pores, and rays are hardly observable to the naked ring (Bhat, 1980; Maier, 2008). However, reaction wood is abundant in Birch and contains a small number of vessels with thin fibres and thick walls compared to regular wood. Thus reaction wood in Birch is heavier, and their lumen is relatively tiny (Luostarinen and Verkasalo, 2000; Ollinmaa, 1955). However, In comparison with regular wood, reaction wood in Birch contains higher cellulose content but lower lignin and extractive contents (Ollinmaa, 1955).

Timber is usually easy to work either with hand or machine tools. Moreover, the medium density of Birchwood ensures some properties such as adequate strength, elasticity, ductility, and flexibility (Salmi, 1987). As a result, Birch is considered an excellent raw material for the furniture and carpentry industry and the construction, packages, and paper pulping industry.

European aspen (*Populus tremula*)

European Aspen belongs to the family *Salicaceae* and Genus *Populus* and originates from colder temperate regions of Europe and Asia. The bark is generally greenish-grey but dark grey in older trees. The heartwood of Aspen is usually light brown, and sapwood colour ranges from pale yellow to nearly white. Wood grain has a uniform medium texture and straight, light, and soft. Aspen does not have any characteristic odour. However, it is vulnerable to insect attacks and labelled as non-durable. Furthermore, Aspen is diffuse-porous with medium pores and narrow rays (Maier, 2008).

Aspen consists of both wet wood and tension wood. Tension wood is one kind of reaction wood and is considered one of the major problems during wood processing as tension wood blunts the cutting tool and produces fuzzy grain (Mackes and Lynch, 2001). At the same time, both the heartwood and sapwood of Aspen contain wet wood. Though Aspen is a hardwood, yet it has lightweight, which is either an advantage or disadvantage, depending on the type of application. As a lightweight, Aspen has better shock resistance compared to other lightweight wood. Moreover, one of the favourable properties of Aspen is that it has slight shrinkage and swelling (Johnson, 1947).

However, Aspen has a relatively low density as well as low compressive strength, hardness; it also a less stiff wood (Johnson, 1947), which limits the application of Aspen in several fields. However, Aspen has wide application in Sawn Products industry, pulp and paper industry, Veneer and Plywood, Particleboard, Oriented Strand board, fuel, etc.

Black alder (*Alnus glutinosa (L.) Gaertn.)*

Black Alder belongs to the family *Betulaceae* and Genus *Alnus*, abundantly found in most parts of Europe, northern Africa, and southwest Asia. Typically, the wet location is a suitable condition for Black Alder. Furthermore, it can grow on poor soil with the association of the bacteria Frankia alni. However, the Bark of young Black Alder is smooth and greenish-brown, but it turns greyish brown with lenticels, short warty, and shallow cracks when growing older. Heartwood and sapwood of Black Alder do not have any visible distinction between them. Black Alder grain has fine and even texture, and grain is usually straight, but in some cases wild or irregular. Black Alder does not have any characteristic odour. However, freshly cut Black Alder logs are vulnerable to staining or decay, and Black Alder is labelled as non-durable (Maier, 2008).

Black Alder is homogenous and diffuse-porous. Black Alder has small vessels with thin walls and countless small medullary rays, which make it grain fine and regular (Claessens et al., 2010). Moreover, Black Alder is light in weight and easy to process. Thus, Black alder is considered a suitable raw material for different applications such as joinery, either as solid wood or veneer, fibre for paper, and energy wood (Claessens et al., 2010). Black Alder is also suitable for Hydraulic work but not suitable when strength is required as it has low strength properties, which means for constructional purpose, this timber is not a good choice.

Grey alder (*Alnus incana (L.) Moench*)

Grey Alder belongs to the family *Betulaceae* and Genus *Alnus*, typically found across the cooler parts of the Northern Hemisphere. It is a small to medium height, short-lived deciduous tree. The bark of Grey Alder is deep grey and smooth (European Commission, 2016). Grey Alder is similar to the common alder (Alnus glutinosa); however, it is slightly darker than common alder and has less economic value compared to common alder. Grey alder is a fast-growing and light-demanding species, and medium or heavy soils are suitable for its growth. However, it can also grow in heavy clay as well as nutritionally deficient soils environment. Grey alder also have the ability to tolerate maritime exposure (Plant For A Future, 2021).

Grey alder consists of six more subspecies, and they are classified based on their locations. One of the significant properties of Grey Alder is, it can fix nitrogen in symbiotic root nodules and improve soil condition (European Commission, 2016), which means it has a great application in land reclamation. Grown Grey Alder wood is suitable for carpentry as it grows straight with a branchless trunk, and grown wood is dense enough. However, the timber is soft and brittle with straight grain and reddish color. Moreover, there is no significant difference between sapwood and heartwood color. Besides carpentry, low-grade Grey alder is suitable for packaging and firewood and smoking chips (PuuProffa, 2021).

Table 2.1.2. 1 exhibits few properties of the four hardwoods used during this research. However, especially for Grey Alder, not much information was available; thus, the table does not exhibit all necessary details on four hardwood species.

Table 2.1.2. 1 Properties of the wood species used in this study (Borůvka et al., 2019; Endel and U, 2006; Maier, 2008)

Wood Properties	Tree species			
	Birch	Grey alder	Black alder	Aspen
Tree height (m)	23-30	15-20	20-25	15-20
Average density (kg/m^3)	630-670	500 - 530	550	490- 540
Elastic Modulus (GPa)	13.96	7.85	11.01	9.75
Tensile strength (MPa)	137	-	-	110
Crushing strength (MPa)	-	-	39.8	35
Compressive strength (MPa)	59.6	-	41.5	50
Modulus of rupture (MPa)	82	-	77.5	62

2.1.3 Veneer producers in Estonia, production process and properties

Veneer production is a part of plywood production, and plywood production in Estonia belongs to international groups. Estonian Plywood AS and Tarmeko Veneer OÜ are the only two companies that belong to Estonian owners. Besides these two local companies, there are several international groups, notably Kohila Vineer OÜ, an associated company of Latvijas Finieris Group, Metsä Wood Eesti AS from Finland’s Metsä Wood Group, OÜ Balti Spoon belongs to Möhring Group, Valmos OÜ owned by Paged Group, and UPM-Kymmene Otepää AS part of UPM-Kymmene Corporation, etc. These companies use several species to produce veneer and plywood, but Silver birch is the dominant species.

However, veneer manufacturing consists of several steps. It starts with the arrival of logs into the log yard of the facilities, where the logs are measured and sorted, then soaked in a pool. After soaking for a pre-decided time, they are debarked and sent for peeling. Then, the veneer is fed into the veneer dryer and then sorted and stored according to the category (Grade A; Grade B and Grade C) and customer requirements (Tarmeko Group, 2020).

Properties of veneer depend on several factors, such as species, veneer thickness, amount of knots, feed speed during peeling, dryer conditions, etc. However, Wood and log characteristics are one of the driving factors that affect the veneer production process and quality. For example, some diffuse-porous hardwoods have a relatively uniform structure which is preferable for the easy cutting operation, drying operation, and processing. Regardless of growth rate, these wood species provide comparatively better quality veneers (LUTZ JF, 1971). However, a uniform or perfect log is considered to have cylindrical forms with pith in the centre and very few defects, but very few logs fall into this category; thus, veneers fluctuate in quality among them. Moreover, logs with smaller diameters and certain logs form such as sweep, tension wood, compression wood, and taper can lower the veneer quality (Lutz, 1974). However, veneers (moisture-proof) are graded on the top layer according to their quality. Table 2.1.3. 1 explains how veneers are graded into different classes.

Table 2.1.3. 1 Veneer quality marks and application area (Debora Grupp AS, 2021; Vineerimaalim, 2020).

Quality mark	Brief description	Application Area
B	Sanded, without branches	Visible surfaces
S	Sanded, without branches, colour difference	Visible surfaces
BB	Sanded, branches filled with patches	Not visible surfaces
WGE	Sanded, without open defects	Construction
WG	Sanded, open defects and branches, cracks	Construction
C	Not sanded, cracks, open branches	Packaging

2.2 Veneer Thickness and Surface Roughness

2.2.1 Veneer Definition and Thickness

The veneer is a thin layer or sheet with uniform thickness finely sliced from wood logs for decoration and construction (Forest Products Laboratory (U.S.), 1962). Veneers are usually referred to as rotary, sliced, or sawed following the method of cutting, such as lathe, slicer, or saw. However, special cutting equipment is available in recent times, allowing the production of veneers with different thicknesses. The loose side of the veneer contains checks, while the opposite side, which does not contain checks, is called the tight side. Typical applications of veneers include wood composites (Plywood, LVL, etc.), construction, decorative inlay, artwork, etc.

Veneer has been sliced into different thicknesses considering the factors such as the species, veneer manufacturer preference, the type of final application or customer's requirements, etc. However, in general, veneer thicknesses vary from 0.64 mm to 7.94 mm. Moreover, wood veneer can be thin as 0.25 mm and thick as 9.53 mm prepared by either rotary lathe or slicer for particular purposes. Still, veneer production with thickness thinner than 0.79 mm by saw is impractical (Forest Products Laboratory (U.S.), 1962).

The most common thicknesses of rotary softwood veneers are 4.76 mm, 3.18 mm, and 2.54 mm, while for hardwood, they are 2.12 mm, 2.54 mm, 3.18 mm, and 6.35 mm. However, in a rotary cut face veneer, the thicknesses vary from 1.27 mm to 0.91 mm. Moreover, sliced veneers are usually produced with thicknesses from 0.79 mm to 1.58 mm for application in the plywood and furniture industry. Furthermore, the traditional sliced face veneer has thickness of 0.91 mm (Forest Products Laboratory (U.S.), 1962).

2.2.2 Properties of Veneer based on the thickness

The properties of veneer sheets depend on several factors such as the anatomical feature of wood, veneer thickness, processing conditions, etc. Moreover, the surface properties of veneer can also be varied due to the factors like mill to mill, log to log, sheet to sheet, etc. One of the most significant properties of wood veneer is surface roughness, as low surface quality of wood veneer influences further manufacturing procedures like glue adhesion, adhesive strength, etc. (Budakci et al., 2007; Li et al., 2018). However, the concept of roughness is not easy to define, though in general, we can say that roughness means a texture that is not smooth but is irregular and uneven. According to ASME B46.1-1995, "the finer irregularities of the surface texture that usually result from the inherent action of some production process, such as machining or wear."

However, several studies show that, based on the increment of veneer thickness, the surface roughness of the veneer also tends to increases (Bekhta et al., 2020; Daoui et al., 2011; Dundar et al., 2008). However, veneer thickness is not the only factor that affects the surface roughness. Still, other factors like cutting speed, knife bevel, etc., also significantly impact the roughness of the veneer, whether the veneer is thin or thick. Dundar et al., (2008) found that surface roughness decrease with the increase of cutting speed, but drying temperature did not have any severe effect. Moreover, they also found that the percentage of the vertical and horizontal opening of the veneer thickness can minimize or increase the roughness of the veneer.

Another important property of wood veneer based on their thicknesses is the formation of lathe checks, e.g., pattern and depth of lathe checks and the frequency of lathe checks. The depth of checks, which has been exhibit as a percentage of the total thickness of the veneer, usually increases when veneer thickness increase (Bekhta et al., 2020; NORRIS et al., 1961). Likewise, the lathe check interval also increases sharply to the thickest veneer (Bekhta et al., 2020; Daoui et al., 2011). The depth of the checks can be up to 70% to 80 % of the veneer thickness based on how thick the veneer is (Rohumaa et al., 2013). Furthermore, the deep, long and large interval between lathe checks also can be produced if the veneer is peeled from logs with a small diameter (Khoo et al., 2019).

2.2.3 Effect of Veneer Properties on end product's

Effect of Thickness

As mentioned earlier, wood veneer obtains some unique properties due to different thickness and other factors. These properties affect physical and mechanical properties to some extent of products prepared from veneer directly or indirectly. Veneer properties such as thickness, lathe checks, surface roughness might affect the one or several properties of manufactured products. A brief description of the effect of these veneer properties has been illustrated below.

Veneer thicknesses affect the manufactured products (LVL, plywood). Specific gravity decreases with the increase of veneer thicknesses (Daoui et al., 2011; De Melo and Del Menezzi, 2014; Khoo et al., 2019). Most of these authors state that LVL or plywood prepared with more thin veneer sheets, which requires more adhesives layers compared to the LVL or plywood prepared with less number of thick veneer sheets. As a result, the amount of adhesives and weight increase, which would increase the specific gravity of the product. Furthermore, a large number of pores and void volume in thick veneer compared to thin veneer also attributed to this finding (Vick, 1999).

Water absorption properties increase with the increase of veneer thickness. Khoo et al. (2019) found that LVL with 3 mm veneer thickness has higher water absorption because of the large number of porosity in 3 mm veneer than LVL with 1 mm and 2 mm veneer thickness regardless of the duration of immersion into water. De Melo and Del Menezzi, (2014) also showed similar results about the water absorption capability of veneers based on thickness. Furthermore, increased cell lumina due to the less specific gravity of thicker veneer is another reason for the higher water absorption rate (Forest Products Laboratory - USDA, 2010).

Glue bond strength, which is crucial to evaluate bonding quality, has been significantly affected by veneer thickness due to the depth of lathe checks and their frequency in thick veneer. Several studies revealed that thicker veneer has deeper and longer lathe checks with lower lathe check frequency which ultimately reduces the glue bond strength (Khoo et al., 2019; Rohumaa et al., 2013). Moreover, Pot et al. (2015) show that bond strength of LVL decrease, especially in edgewise direction when prepared with thicker veneer.

The explanation of why lathe checks of thicker veneer tend to reduce the bond strength was illustrated by (Khoo et al., 2019). According to them, a thin veneer has fewer deeper checks; thus, adhesives can fill these checks and reduce the effect of checks. Furthermore, in comparatively thin veneer, the existence of lathe check frequency in the loose side of the veneer is higher, which improves the wettability of veneer, and increased wettability of veneer allows the adhesive to penetrate thoroughly and strengthen the bonding. However, up to a certain point, the bond strength will increase along with the veneer thickness reduction. A zone of resin-impregnated wood is formed when adhesives penetrate wood fibres. This zone has higher strength properties compared to the original veneer. So, when the thickness of the veneer is too small or less than twice the distance of penetration of the resin, it limits the penetration of adhesive on the veneer surface and prohibits the further increment in strength.

Effect of Surface Roughness

Veneer surface roughness is one of the significant factors that can affect bond strength. However, several studies show that both macro and micro veneer roughness coexist (Stumbo, 1963) due to several mechanical processes such as feed rate, knife sharpness, and angle veneer thickness and anatomical factors. In general, it has been assumed that bonding improved with the roughening of a surface (Gent and Lai, 1995). Furthermore, Adhesives prefer porous surface over the smooth surface to form a strong bond (Packham, 2003). However, Marra, (1992) states that if the surface roughness is too high, it hinders the adhesive from making contact with the wood surface. As a result, the poor quality of glue bond formed, supported by several other researchers (Aydin, 2004; DeVallanc et al., 2007; Follrich et al., 2010).

The reasons behind this statement were further described by DeVallanc et al., (2007) that, when surface roughness increases, it reduces the actual surface area and thus in the contact area, directing to the declination of the constructive bond line. Furthermore, the presence of peaks and valleys on the rough surface, restricted bonds only among peaks weaken the bond strength (Neese, 1997). Due to higher roughness, gaps occur in the bond line, which decreases the cohesive strength by acting as points of crack initiation and propagation (Follrich et al., 2010). Several other researches also show that rough surface is responsible for desiccation, over penetration, or starving of the adhesive (Nees et al., 2004). Moreover, as a result of machining, a weak boundary layer is formed with the properties such as loosely adhered cells and cell wall fragments and affect the bond line firmness, and further affects the adhesive penetration into the wood surface by acting as a barrier (Stehr et al., 1999; Stehr and Johansson, 2000).

Moreover, rough veneer also has a notable influence in reducing wood failure percentage (Nees et al., 2004). DeVallanc et al. (2007) worked with Douglas-fir plywood, and observed that the specimens obtained the highest average percentage wood failure with smooth surface roughness, followed by the specimens with an intermediate and rough surface.

2.3 Wood Adhesives and Their Interaction with Wood Species

The adhesive itself does not express any meaning in general rather; represents several materials that are gluing different substances with various mechanisms (Rath and Müller, 2005). Nevertheless, in a broad sense, adhesives can be described as a social substance in a mixture form either in a liquid or semi-liquid state, can bond with a surface permanently by following a process (Dinte and Sylvester, 2018). In contrast, the term adhesion refers to a process that explains the interaction between the adhesive surface and substrate surface. Polymeric materials (both natural and synthetic) are typical raw materials applied as adhesives. However, synthetic materials are widely used in the adhesive industry.

The classification of adhesives is quite complex and can be illustrated with several factors. However, in general, adhesives may be grouped as organic or inorganic considering the factors such as origin, method of adhesion, chemical basis, or end application (Mays and Hutchinson, 2009). However, in the wood industry, synthetic and naturally obtained resins are frequently used. The most common synthetic resins used in the wood industry are urea-formaldehyde and phenol-formaldehyde, while natural resins such as soy protein-based adhesive, tannin, and lignin resins also have application in the wood industry (Zhou and Du, 2018).

2.3.1 Bond Formation

Adhesion is a trans disciplinary science that covers several scientific disciplines like different branches of chemistry, rheology, mechanics, etc. (Kumar and Pizzi, 2019). Understanding the adhesion mechanisms is essential for woodworking, as wood properties are complex, making it challenging to determine which adhesives work better. Thus, understanding the essence of adhesions is essential as it will enable acknowledging the factors dominating the performance of the bond (Frihart, 2013).

Adhesion is a situation in which distinct surfaces or particles adhere with each other due to interfacial forces of either valence forces or interlocking action nature or both (Kumar and Pizzi, 2019). At the same time, cohesion is the state when similar molecules attract mutually and stick together. The shape and structure of molecules are driving factors behind cohesive force (Ülker, 2016).

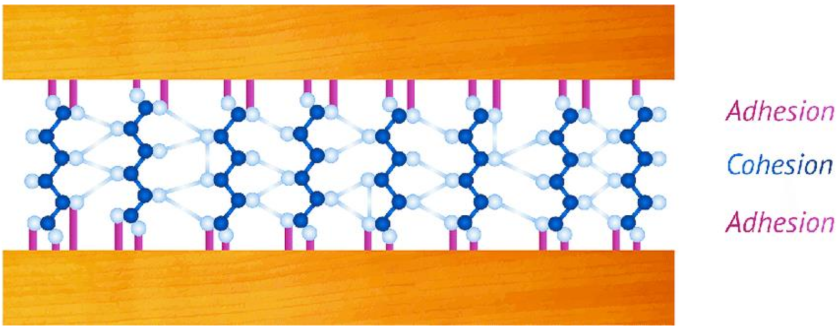


Figure 2.3.1. 1 Chain link for adhesion and cohesion (Ülker, 2016).

However, the process of adhesion and cohesion is referred to as the bond formation, or more generally, the result of bonding of two substrates with a glue that functions through adhesion and cohesion (Kumar and Pizzi, 2019). Furthermore, in-depth, the process of adhesion and cohesion indicates the attraction between the substrate and the adhesive along with the cohesive strength of the adhesive (Hunt et al., 2018). However, the adhesive strength depends on the interactions, both physical and chemical, between substrate and adhesive, and between adhesive and substrate molecular level contact is essential for better adhesion (Hunt et al., 2018).

However, the responsibilities of adhesives are to transfer and allot loads between wood components and improve the strength and stiffness of wood products (Browne and Brouse, 1929) and which can be achieved by three basic types of adhesions such as specific adhesion, mechanical adhesion, and effective adhesion (Kumar and Pizzi, 2019). Specific adhesion occurs between adhesive and adherent by chemical reaction, and the molecular attraction between the surfaces can be ionic, covalent, and influenced by any other intermolecular forces (Frihart, 2004; Kumar and Pizzi, 2019). While Mechanical adhesion involves mechanical anchorage and effective adhesion merge mechanical and specific adhesion for better bonding strength (Kumar and Pizzi, 2019). Several adhesion theories have been emphasized. However, according to Schultz and Nardin, (2003), the main adhesion theories are mechanical interlocking, electronic or electrostatic theory, adsorption or wetting theory, diffusion theory, chemical bonding theory, and theory of weak boundary layers and interphases. However, the absorption or wetting theory has been acknowledged extensively as more suitable to wood polymer adhesion as it clears the adhesion introduce by the intermolecular forces (Gray, 1962).

2.3.2 Penetration Process of wood adhesives

Several types of wood adhesives are available nowadays, and they have been utilized widely in the wood industry for wood-based products (Kamke and Lee, 2007). However, the essential purpose of these adhesives is to glue wood panels and manufacture composites with several desired properties (Kamke and Lee, 2007). However, these desired properties of wood composites dramatically depend on the interaction between adhesive and wood (Follrich et al., 2010). Thus, Adhesive vs. Wood bonding interaction is necessary to characterize as it reveals important information about the bonding mechanism (Stelte et al., 2011).

The adhesives can soak the wood layers and go along to the inner wood structure (Kamke and Lee, 2007) due to high porosity and surface energy and better wettability properties inherited by wood surface (Gavrilovic-Grmusa et al., 2008). This incident has been levelled as adhesive penetration, which has an extreme impact on bonding properties.

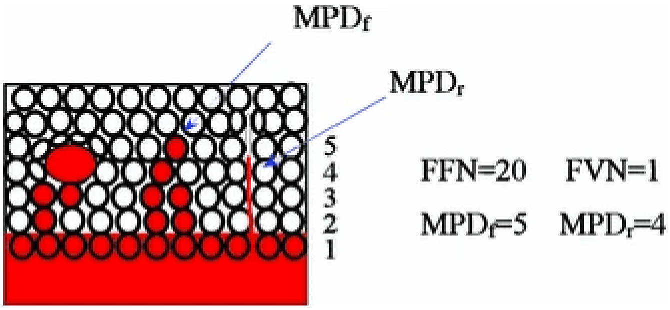


Figure 2.3.2. 1 Schematic configuration of adhesive penetration pattern parameters(Edalat et al., 2014)

However, the penetration of adhesives into wood is not always uniform; instead, adhesives tend to penetrate in different depths, which might be fully or partially filled vessels or interaction on wood cells (Gavrilovic-Grmusa et al., 2008). Moreover, internal wood structure (vessels or lumens) has a particular arrangement towards the longitudinal direction, which allows the movement of resins in this direction of wood more appreciable than in other directions (Kamke and Lee, 2007). However, the penetration depth of adhesive into wood has a significant relationship with the wood products performance, as insufficient penetration of adhesive will reduce the bonding strength while excessive penetration will defect the bond line and increase the production cost (Edalat et al., 2014; Paris and Kamke, 2015).

The adhesive penetration into wood has been categorized into two sub-groups, such as micro-scale gross penetration and nano-scale cell-wall penetration (Gavrilovic-Grmusa et al., 2008; Ülker, 2016). However, these two distinct types of adhesive penetration, affected by several factors, provide different properties to the wood products.

Gross penetration occurs to micro-scale, where liquid adhesives flow into the wood pores and capillary structure and fill cell lumens entirely or partially (Gavrilovic-Grmusa et al., 2008; Ülker, 2016), with two different driving forces such as hydrodynamic flow and capillary action (Kamke and Lee, 2007). Gross penetration is usually controlled by different factors, such as pore size, the viscosity of adhesive, applied pressure, and wetting nature (Hunt et al., 2018). Furthermore, gross penetration may occur with most adhesive with low viscosity (Qin et al., 2016). However, cell wall penetration occurs when adhesives diffuse from outside to the cell wall or flow into micro-fissures (Paris and Kamke, 2015; Ülker, 2016), consequently lowers the cell wall swelling and increase strength (Hunt et al., 2018). Nevertheless, cell wall penetration only occurs with the adhesives formulated with low molecular weight components (Qin et al., 2016).

2.3.3 Factors Affecting Adhesive Penetration into Wood

Several factors related to the wood properties, adhesive properties, or processing conditions can vastly affect the wood adhesive penetration. Paris and Kamke, (2015) found that, in softwood; adhesive penetration was much faster than hardwood. This difference in penetration of adhesives between softwood and hardwood is associated with their structural properties. The tracheid in softwood is highly aligned and ordered also pore size is much more uniform, which enables the faster penetration of adhesive (Ansell, 2015), while hardwood vessels are large and randomly distributed, resulting in the adhesive penetration much more random (Ansell, 2015; Ferdosian et al., 2017). The pore size also plays a role in adhesive penetration. Wang and Yan, (2005) experimented the effect of pore size of birch and aspen with PF adhesive and found that PF adhesive penetrates readily when the pore size is bigger.

Surface roughness is also another major factor that affects adhesive penetration into the wood as surface roughness is correlated to the contact area between the wood specimen and adhesive (Ferdosian et al., 2017). Wood surfaces with better wettability can have deeper adhesive penetration as this property allows smooth flow and motion of liquid adhesive (Wei et al., 2012). Furthermore, growth orientation also impacts adhesive penetration and bond strength, like when grain angle increases, bond strength decreases (Follrich et al., 2007). Besides wood surface properties, certain adhesive properties also have an impact on adhesive penetration. Thick bond line and partial penetration can be occurred due to the high viscosity of the adhesive, and particular filler can increase the viscosity of adhesive (Veigel et al., 2011). Adhesives with smaller molecular weight might have better penetration than adhesives with large molecular weight (Johnson and Kamke, 1992; Laborie et al., 2006).

Moreover, processing conditions also have detectable effects on adhesive penetration. Cheng and Sun, (2006) demonstrated that low pressure and high pressure lead to poor adhesive penetration, as low pressure means lack of contact between wood and adhesive, while high pressure wrecks the interlayers.

2.3.4 Adhesives, Their Properties and Bonding with Wood

Polyvinyl acetate (PVAc)

PVAc is one of the water-borne adhesives invented at the beginning of the 20th century. However, the composition of PVAc available at present is different from the glue composition from the early stages. Commercially produced PVAc has white colour. It is a viscous liquid and has resistance to environmental factors. PVAc is a one-part adhesive and has a longer pot life (Tout, 2000).

PVAc is produced with polymerization of vinyl acetate ($CH_3CO_2CH=CH_2$). First, Vinyl acetate is prepared from ethylene. Then, the Vinyl acetate monomers are polymerized while dispersed in water. As a result, milky white emulsion formed, which can be processed into latex paints or white or Elmer’s glue later (Petković et al., 2019).

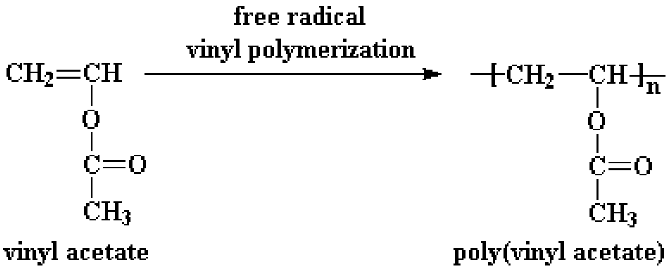


Figure 2.3.4. 1 Homopolymerization process of Polyvinyl acetate (Polymer Science Learning Center, 2021).

PVAc has been considered as a flexible resin as it is a linear polymer and contains an aliphatic backbone. Moreover, being water-borne, PVAc displays smooth flow into exposed cell lumen but may not penetrate cell walls because of their high molecular weight. However, for better interfacial adhesion with diverse fractions of the wood, many hydrogen bonds are necessary to form by adhesive. PVAc can form the required number of hydrogen bonds due to its flexible backbone and high content of acetate groups (Frihart, 2013). However, there are optimum bonding conditions for PVAc, such as thin glue lines and low moisture contents; thus, the setting time of PVAc depends on the glue thickness and components moisture content (Frihart, 2013; Tout, 2000). However, in general, it is expected that in 15 minutes at normal ambient temperatures decent amount of bond strength will be developed with modern PVAc glue. Glue line of PVAc is thin and almost invisible. Moreover, PVAc softens when temperature increases, limiting its pressing temperature up to 80^{o}C and also tends to creep under pressure (Conner, 2001; Tout, 2000). It is possible to overcome the disadvantage of creeping by crosslinking and convert it into thermosets. However, in the wood industry, PVAc has a wide range of applications, including wood veneer, edge gluing, furniture industry, and construction engineering.

Polyurethane (PU)

Polyurethane (PU) is a widely used resin in the wood industry for high adhesive, cohesive strength, formulation flexibility, low cost, high impact resistance, and ability to bond many substrates (Bronia Stefanowski et al., 2018). Polyurethanes are polymers that contain the urethane ($–NH-CO_2$) group in the polymer chain. The chemistry of the PU's was first investigated in 1937 (Kumar and Pizzi, 2019). An early prototype was produced by reacting toluene diisocyanate reacted with glycols. Later in the early 1970s, the German particle-board Industry used isocyanate, specifically 4,4′-methylene diphenyl isocyanate binders in composite panels (Kumar and Pizzi, 2019). From then, the PUs based on aromatic monomer 4, 4′-diphenylmethane diisocyanate

(MDI), and the polymeric MDI (pMDI) became one of the most popular wood binders in the forest industry.

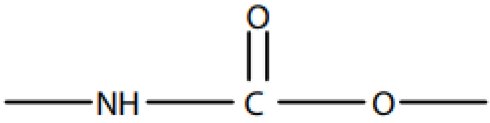


Figure 2.3.4. 2 PU monomer

Isocyanates and Polyols are the two primary raw materials for PU adhesive (Pizzi and Mittal, 2011). However, the forest industry mainly employed isocyanate-based PU adhesives. Almost 74% of isocyanate-based PUs are made up of MDI and pMDI (Sonnenschein, 2015). Production of MDI consists of three essential steps, namely nitration, reduction, and phosgenation. By fusing aniline with formaldehyde, the plyometric MDA has been formed, which later has been phosgene to form MDI oligomers which later has been distilled to produce MDI and pMDI. Fig 2 illustrated a simplified block diagram of MDI production (Sonnenschein, 2015).

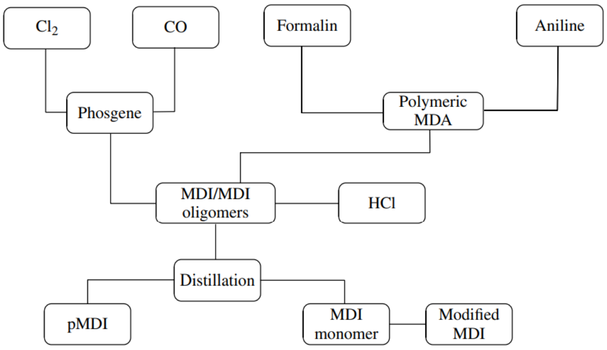


Figure 2.3.4. 3 Simplified block diagram for production of monomer and polymeric MDI (Sonnenschein, 2015)

One-part solvent less and Two-part waterborne are the two most common types of PU adhesive format for wood binding. The ability of isocyanate to react with amine and water is the key to use it for wood binding application. Wood contains a substantial amount of hydroxyl group with which isocyanate is able to react. Isocyanate creates amine by reacting with water (moisture in the wood) and later produced urea-linked hard segments by reacting with amine (Kumar and Pizzi, 2019). The pMDI can penetrate the cell wall and can flow into the microvoids of the fracture. In addition, it can travel ~1 mm from the applied radial wood surface, which makes it a perfect candidate to create a covalent bond with the wood (Kumar and Pizzi, 2019) Higher amounts of isocyanates lead to hard and brittle bond lines. The pot life is determined by the reactivity, temperature, and the use of catalysts. The pot life can vary between 0.5 and 24h. The cure at room temperature is completed within 3 to 20h (Dunky and Pizzi, 2002).

Phenol formaldehyde adhesive

Phenol-Formaldehyde (PF) resins make superior wood adhesives and are widely used glues for construction-grade wood panels such as plywood and oriented strand boards. Phenol-Formaldehyde reacts with natural phenol-like lignin found in wood that strengthens the wood bond. PF resins are synthetic polymers produced from the reaction between formaldehyde and phenol or substituted phenol. Novolacs and resols are the two types of formulation methods for PF preparation (Conner, 2001; Kumar and Pizzi, 2019). In the novolacs method, the acid catalyst has been used with molar excess of phenol over formaldehyde.

Nevertheless, in the resols method, molar excess of formaldehyde over phenol under alkaline catalyst is used (Conner, 2001). Also, the novolacs method employs formaldehyde-releasing reagents like hexamine or paraformaldehyde for PF polymerization. On the other hand, heating or acid catalyst are used for curing in resols method. PF adhesives are very popular in the forest industry due to their thermally stable, water-resistant features and superior mechanical properties (Kumar and Pizzi, 2019).

Phenol-formaldehyde is formed by step-growth polymerization. Typically, phenolic resin is made in batches. The reactor must be equipped with heating and cooling facilities. The major elements of the manufacturing chamber are an agitator, a reflux condenser, vacuum equipment. Firstly, molten phenol and formalin, along with water and methanol, are put into the reactor chamber with a specific molar proportion between 1:1.1 and 1:2. Then based on the PF type, acid or alkaline catalysts are introduced to the reaction. For example, an alkaline catalyst such as sodium hydroxide is added to the batch for resol-type resin production. Heat control is one of the prime concerns for PF production. Thus a cooling mechanism is implemented in the reactor to maintain the chamber temperature below 95°C to 100°C. Reaction time is depended on various parameters like the pH, the phenol/formaldehyde ratio, the presence or absence of reaction retarders, and the temperature of the reaction (Banks, 1995).

PF adhesive is a water solution of oligomers with different molecular weight and shape (Biziks et al., 2019), while wood is a natural and porous substance, has two different types of internal voids such as large voids (cell lumina, pit openings) and cell wall microvoids (Rittiphet et al., 2021). However, during the penetration process of PF into the wood, the oligomers first reach the pore system (lumen, vessels, ray, etc.) and disperse into the cell wall of fibre lumen and slowly take over the space of cell wall microvoids by replacing the molecules of the cell wall. As a result, an everlasting expansion or bulking of cell walls resulted (Biziks et al., 2019), The depth of the cell wall penetration by PF is affected mainly by the PF resin oligomers size (Hill, 2006). Furthermore, the importance of molecular weight and size of a resin on penetration was further illustrated and suggested that the amount of resin in the cell wall of lumen would considerably alter the properties of wood (Ryu et al., 1993).

Furthermore, due to several forces and functional groups, the interaction between wood and PF adhesive’s chemical groups is complex. However, the interactions of PF adhesive with wood cellulose and lignin are considered as most crucial interaction (He and Riedl, 2004). Though etherification of cellulose with formaldehyde in an acidic state is possible (Kottes et al., 1986; Myers, 1985) but with wood cellulose, either no chemical reaction or minor degree of reaction can occur with formaldehyde regardless of the natural or alkaline conditions (Myers, 1985). Unlike cellulose, wood lignin goes to the reaction with formaldehyde and forms methylolated lignin with lower activation energy (Gardner and McGinnis, 1988).

Thus, PF has lower reaction enthalpy with the wood substrate, which means there might be no reaction that occurred during the curing reaction of PF (He and Riedl, 2004) and further indicates the theory of wood adhesive bond explained by multiple secondary force interactions (He and Riedl, 2004). Usually, PF is used to modify wood or wood products by treating them with water-soluble PF resin, which has been considered an effective method to upgrade the dimensional stability and durability of wood and wood products.

Lignin-Based Phenol-Formaldehyde adhesive

In-plant world, besides cellulose, lignin is the most profusely polymeric material. Lignin is usually acquired as a by-product of wood pulping from paper production. However, lignin is a very complex and irregular polymer, elaborately a large three-dimensional polymer with phenyl propane units (Conner, 2001). However, lignin’s structure is more or less homogeneous to the structure of PF (Tejado et al., 2007; Turunen et al., 2003). Thus, lignin is used during the PF adhesive synthesis as a phenol substitute. However, the inactivity of lignin is lower than phenol; thus, it requires modification to enhance reactivity (Forss and Fuhrmann, 1979). For chemical modification, the phenolic and hydroxyl groups of lignin are usually used as reactive sites. Methylolation (Vázquez et al., 1999), demethylation (Olivares et al., 1988), and phenolate (Lee et al., 2012) are utmost modification methods. In methylolation minimum increase in activity occurs, while demethylation increase the activity but has limited application.

However, in wood adhesive, lignin by itself does not have any advantages in terms of quality, reactivity, or colour. Furthermore, as wood adhesive, the profound drawbacks of lignin's are slow hardening due to low reactivity and chemical variation in feedstock (Dunky and Pizzl, 2002).

Furthermore, LPF has a low level of substitution of cell wall molecule and higher adhesive viscosity. LPF also decreases curing rate, and the solubility of LPF depends on the type of lignin. However, LPF impregnation into wood cell walls can improve the thermal properties, modulus of elasticity, water resistance, and usually, LPF provides Good bonding strength (Ferdosian et al., 2017).

3 MATERIALS AND METHODS

This chapter provides an overview of the materials and methods applied for this research, such as veneer production procedure, samples preparation scheme, the procedure of veneer surface roughness measurement, preparation of adhesives, gluing and pressing, and conducting lap shear test.

3.1 Materials

The primary materials used for this research were logs from four hardwood species (Black Alder, Grey Alder, Birch, and Aspen). Adhesives for bond formation testing were the following: polyvinyl acetate, and polyurethane adhesives from Kiilto Eesti OÜ, as well as phenol formaldehyde and lignin-based phenol-formaldehyde adhesives from Prefere Resins Finland Oy. All logs were freshly felled in November, 2019, at Piirsalu, Lääne County, Estonia, by State Forest Management Centre. Grey alder and black alder trees were cut into logs with nominal length of 2.7 m, and for birch and aspen a length of 3.2 m. The average density of black alder was 550 kg/m^3, for grey alder it was 500-530 kg/m^3, while for birch, and aspen the average density was 630-670 kg/m^3 and 490-540 kg/m^3 respectively (Maier, 2008). Logs with quality classes B and C were randomly selected for the research. The weighted (by area) average stand age of the birch trees was 81 years, grey alder 55 years, black alder 70 years, and aspen 74 years.

3.2 Veneer Production

The following section contains details of the Veneer production process and machines used during the process and their technical data information. A general scheme of veneer production is illustrated in the Figure 3.2. 1.

Figure 3.2. 1 A general scheme of veneer production

Less defected and better-shaped logs of four species have been selected from the log yard located next to the Tallinn University of Technology's Laboratory of Wood Technology one after one for soaking. Before soaking, the logs were cut to peeler blocks with the length of 1.2 m to fit into the soaking bath. The soaking bath's temperature was maintained at 40°C for all peeler blocks of four species and soaking time was approximately 24 hours. The soaking tank was filled with water, and the tank's cover was remained closed during soaking. Furthermore, two peeler blocks of the same species were soaked together at a time.

Table 3.2. 1 Soaking Tank specifications

	Description of the Soaking Tank
	▪ Dimensions: 150x220x160 cm ▪ Weight: 980 kg ▪ Electricity demand: 3x32 A ▪ Heating Power: 12 KW ▪ Capacity: Maximum 10 logs with a length of 120 – 130 cm

After soaking, the peeler blocks were lifted out from the soaking tank for debarking. Debarking was done by hand using a carved draw knife, and a small hand axe was used to remove the knots from the peeler blocks. The peeler block's moisture content was calculated from three different places with Gann Hydromette HT 85 T during the debarking operation, as well as the initial temperature of the peeler blocks was measured with a dual laser infrared thermometer. After the debarking, peeler blocks were inspected with a metal detector to ensure that there was no metal inside the peeler blocks to avoid the destruction of the peeling blade and machine, and then the peeler blocks were lifted to the peeling machine manually.

Figure 3.2. 2 Moisture Content and Temperature Measurement

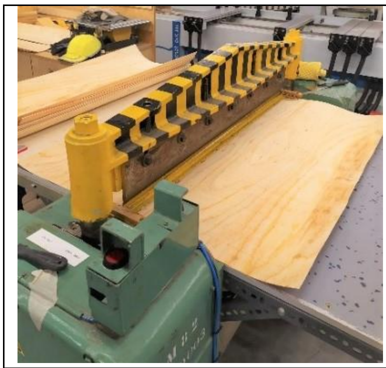
Lathe Raute 3HV66 machine was used for peeling operation by the operator. During this process, the peeler blocks were secured between the lathe spindles and were rotating at high speed. The veneer strips were peeled from the peeler blocks by moving the knife closer to the peeler blocks. The peeling speed was maintained at 60m/min. Four different thick (1.0 mm; 1.5 mm; 2.6 mm, and 3.0 mm) veneer sheets were peeled during the peeling operation.

Table 3.2. 2 Veneer peeling machine specifications

	Description of the Lathe Raute 3HV66
	▪ Dimensions:850x290 x400 cm ▪ Weight: 17000 kg ▪ Electricity demand: 3x400 A (lathe and hydraulics) ▪ Lathe motor power: 66 kW ▪ Offer length: 120-130 cm ▪ Offer diameter: max 60 cm ▪ Veneer sheet thickness: 0.8 to 30 mm

The freshly peeled veneer rolls were then inspected for visible damages to cut them out. Then, the veneer sheets were cut with the veneer guillotine Wärtsilä VAL1000CP. The size of each veneer sheet was 900x450 mm. After cutting the veneer sheet, they were marked on the tight side with a unique code to be identified easily later. A unique sample code is such as 1.0 BA.1.1.40.170, where:
1.0 – Thickness of veneer
BA – Black Alder (Wood Species)
1 – Log Number
1 - Veneer Sheet Number
40 – Soaking Temperature
170 – Drying Temperature

Table 3.2. 3 Veneer guillotine Wärtsilä VAL1000CP specifications

	Description of Veneer guillotine Wärtsilä VAL1000CP
	▪ Dimensions: 180x170x115 cm ▪ Weight: 150-200 kg ▪ Require compressed air to operate

The next operation was veneer drying with Raute veneer drier. At first, one veneer sheet was dried for a certain time based on the veneer thickness at 170°C. Then three small samples were prepared from that dried veneer to measure the moisture content. The moisture content was measured by the oven-dry method at an elevated temperature of 130°C. If the measured moisture content was in-between the acceptable range (4.5% ± 1.5%), then the rest of the veneer sheets were dried for that particular time.

On the other hand, if the measured moisture content was not in-between the acceptable range (4.5% ± 1.5%), then the initial drying time was either increased or decreased one or several times to achieve an acceptable range of moisture content. Following this procedure, the final drying time was determined for different veneer thicknesses of different species. Appendix 1 contains the technical data collected during veneer peeling and drying.

Table 3.2. 4 Raute Veneer Drier specifications

	Description of Raute Veneer Drier
	▪ Dimensions: 320x200x200 cm ▪ Weight: 1200 kg ▪ Electricity demand: 3 x 32 A ▪ Require compressed air and water vapour to operate

3.3 Sample Preparation

The exact numbers of samples were cut with a saw machine from veneers produced from two different logs of each species. Samples were prepared from the maximum homogenous area of veneer sheets with the least amount of defect. The sample size was 120 mm parallel to the grain and 20 mm across the grain, followed by the test standard ASTM D7998 - 19. After cutting, the samples were marked and were placed in the conditioning room for further experiment. However, a sample cutting plan was prepared to have a clear concept of preparing samples from veneer sheets. Figure 3.3. 1 illustrates the cutting plan in detail.

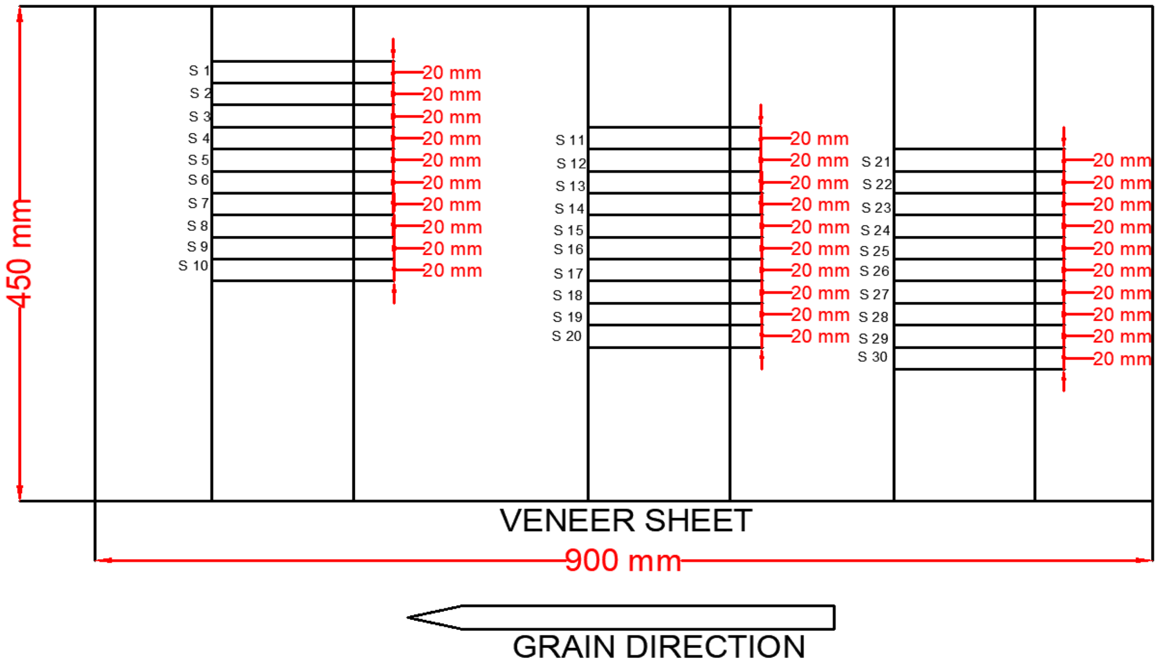


Figure 3.3. 1 Sample cutting plan

Table 3.3. 1 Samples for surface roughness measurement

Code	Sample Description	No. of Samples from One Veneer Sheet	No. of Veneer sheet from one Log			No. Of Samples from one log
			From Bark Side	From Middle	From Pith Side	
SR	Surface Roughness	30	2	2	2	180

Figure 3.3. 2 Sample preparation with saw machine

3.4 Procedure of Surface Roughness Measurement

The surface roughness of samples was measured using Mitutoyo Surftest SJ-210 by following test standard ISO 4287:1997. A wooden board was prepared to set up the samples based on their thicknesses so that that test can be conducted smoothly. Moreover, clamps were used so that the samples do not move during the test. Before start measuring the roughness, the Surftester was always appropriately calibrated, followed by manufacturer instruction. The stylus of the Surftester was placed inside the 5 mm bond area of each sample (Figure 3.4.1), and the test was carried out. The incorporated software was used to operate the machine and collect the test results.

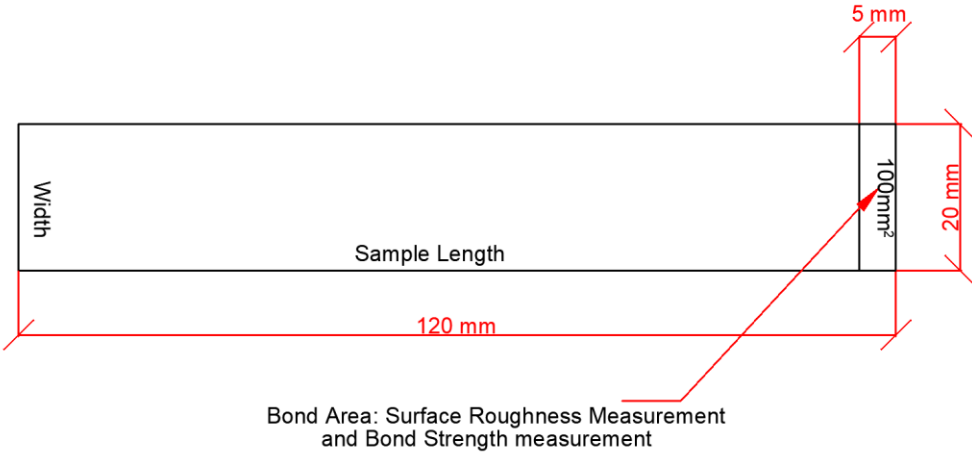


Figure 3.4. 1 Area for surface roughness and bond strength measurement

Figure 3.4. 2 Surface roughness measurement procedure

3.5 Test Plan for Bond Strength Test

The bond strength of veneer samples of different species and thicknesses glued with four different adhesives (PU, PVAc, PF and LPF) were tested by following the test standard ASTM D7998 – 19; Standard Test Method for Measuring the Effect of Temperature on the Cohesive Strength Development of Adhesives using Lap Shear Bonds under Tensile Loading. The test procedure consists of several steps, such as veneer samples conditioning, glue preparation, pressing, again conditioning of samples, and finally bond strength test.

3.5.1 Glue Preparation

The producer of the resin, Kestopress 3200 V- PVAc, was Kiilto Eesti OÜ. Kestopress 3200 V- PVAc is one component adhesive; thus, no further steps are required for mixing this glue. However, during the application, the manufacturer instruction was followed strictly. While, for Polyurethane (PU), Kestopur 200/90 and hardener from Kiilto Eesti OÜ were used, and this glue is a two-component glue, thus requires mixing. The ratio of the solid content of PU and Hardener was determined based on the manufacturer's instruction, which is 5 parts of adhesives and 1 part of hardener. The recipe of 100 g of this resin is shown in Table 3.5.1. 1.

Table 3.5.1. 1 Mixing Recipe of PU

Polyurethane (PU)	
Components	Percentage (%)
Kestopur 200/90	83.33
Kestopur 200/S hardener	16.67

The producer of Phenol-Formaldehyde (PF) and Lignin-based phenol-formaldehyde (LPF) resins and Hardener was Prefere Resins Finland Oy. The mixing recipe of PF and LPF is shown in Table 3.5.1. 2 and Table 3.5.1. 3, respectively.

Table 3.5.1. 2 Mixing Recipe of PF

Phenol Formaldehyde (PF)	
Components	Percentage (%)
Resin 14J021	68
Hardener 24J662	14
Water	18

Table 3.5.1. 3 Mixing Recipe of LPF

Lignin-based phenol–formaldehyde (LPF)	
Components	Percentage (%)
Resin 14J021	73.31
Hardener EXPH 9500	13.20
Water	13.49

The resin was mixed by using the Velp stirrer (Figure 3.5.1. 1). At first, the resin was poured inside a bucket, and then the bucket was placed under the stirrer. The stirrer was then turned on, and later the water and hardener were added into the resin in a small amount at a time. The hardener and water were mixed slowly into the resin to avoid small clumps of hardener inside the adhesive.

Figure 3.5.1. 1 Mixing of adhesive

3.5.2 Gluing and Pressing

The overlapping area of the samples was 5 mmx20 mm= 100 mm^2. The adhesive spreading rate was 126 g/m^2. The Adhesive was applied to the sample's surface in two drops of 6.3 microliters using a micropipette (Rainin™ Pipette). Then, another pre-selected sample was scrubbed with the main sample within their bond area to ensure uniform distribution of Adhesive all over the bond area (Figure 3.5.2.1). Then the samples were pressed in CARVER hot-press.

Figure 3.5.2. 1 Adhesive drops and Uniform distribution of Adhesive

The pressing time for the pressing operation in CARVER hot-press, was determined by combining the results from temperature testing for different veneer thicknesses and curing time for each different adhesive suggested by the manufacturer. The temperature testing was conducted with thermocouples for each different veneer thicknesses, and the time was recorded when the thermocouple reached the desired temperature.

Figure 3.5.2. 2 Temperature Testing with Thermocouples

However, a total of six samples were pressed at a time. During pressing, two aluminium plates were used to hold the samples straight. The applied pressure was 1.8 MPa.

Figure 3.5.2. 3 Sample Pressing at CARVER hot-press

Furthermore, Table 3.5.2. 1, Table 3.5.2. 2, Table 3.5.2. 3, and Table 3.5.2. 4 consist of more detail information about gluing and pressing conditions with four different adhesives (PU, PVAc, PF and LPF).

Table 3.5.2. 1 Gluing and Pressing Parameters for PU Resin

Resin	PU			
Veneer Species	Black Alder; Grey Alder; Birch; Aspen			
Veneer Samples Thickness	1.0 mm, 1.5 mm, 2.6 mm, 3.0 mm			
Number of Samples	15/Species/thickness			
Amount of Resin, g/m^2	126 g/m^2			
Curing Temperature	70°C			
Pressing force	1.8 MPa			
Pressing Time	Thickness	Measured Press Time	Curing time for glue	Total Pressed time
	1.0 mm	100 sec	900 sec	1000 sec
	1.5 mm	120 sec	900 sec	1020 sec
	2.6 mm	170 sec	900 sec	1070 sec
	3.0 mm	195 sec	900 sec	1095 sec

Table 3.5.2. 2 Gluing and Pressing Parameters for PVAc Resin

Resin	PVAc			
Veneer Species	Black Alder; Grey Alder; Birch; Aspen			
Veneer Samples Thickness	1.0 mm, 1.5 mm, 2.6 mm, 3.0 mm			
Number of Sample	15/Species/thickness			
Amount of Resin, g/m^2	126 g/m^2			
Curing Temperature	80°C			
Pressing force	1.8 MPa			
Pressing Time	Thickness	Measured Press Time	Curing time for glue	Total Pressed time
	1.0 mm	100 sec	40 sec	140 sec
	1.5 mm	120 sec	40 sec	160 sec
	2.6 mm	170 sec	40 sec	210 sec
	3.0 mm	195 sec	40 sec	235 sec

Table 3.5.2. 3 Gluing and Pressing Parameters for PF Resin

Resin	PF			
Veneer Species	Black Alder; Grey Alder; Birch; Aspen			
Veneer Samples Thickness	1.0 mm, 1.5 mm, 2.6 mm, 3.0 mm			
Number of Sample	15/Species/thickness			
Amount of Resin, g/m^2	126 g/m^2			
Curing Temperature	130°C			
Pressing force	1.8 MPa			
Pressing Time	Thickness	Measured Press Time	Press time for glue	Total Pressed time
	1.0 mm	100 sec	240 sec	340 sec
	1.5 mm	120 sec	240 sec	360 sec
	2.6 mm	170 sec	240 sec	410 sec
	3.0 mm	195 sec	240 sec	435 sec

Table 3.5.2. 4 Gluing and Pressing Parameters for LPF Resin

Resin	LPF			
Veneer Species	Black Alder; Grey Alder; Birch; Aspen			
Veneer Samples Thickness	1.0 mm, 1.5 mm, 2.6 mm, 3.0 mm			
Number of Sample	15/Species/thickness			
Amount of Resin, g/m^2	126 g/m^2			
Curing Temperature	130°C			
Pressing force	1.8 MPa			
Pressing Time	Thickness	Measured Press Time	Press time for glue	Total Pressed time
	1.0 mm	100 sec	240 sec	340 sec
	1.5 mm	120 sec	240 sec	360 sec
	2.6 mm	170 sec	240 sec	410 sec
	3.0 mm	195 sec	240 sec	435 sec

3.5.3 Bond Strength Testing

After gluing and pressing, the specimens were placed inside a conditioning chamber at 20°C temperature and 65% humidity. The specimens were kept inside the conditioning chamber for at least 48 hours before evaluating the bond strength by lap shear test. The lap shear test was conducted with universal testing machine Zwick/Roell Z050 by following Test standard ASTM D7998 – 19. The specimen was attached between the clamps of the Universal testing machine, and the clamps were powered by compressed air to avoid the specimen slipping from the clamp's grip. Moreover, the Universal testing machine's clamps were set up in certain ways to avoid compression force (pre-load) when the clamps hold the sample. The distance between the two clamps of the Universal testing machine was 170 mm, and the test was carried out at a speed of 2 mm/min. Figure 3.5.3. 1 exhibits the bonding quality testing with Zwick/Roell Z050 machine.

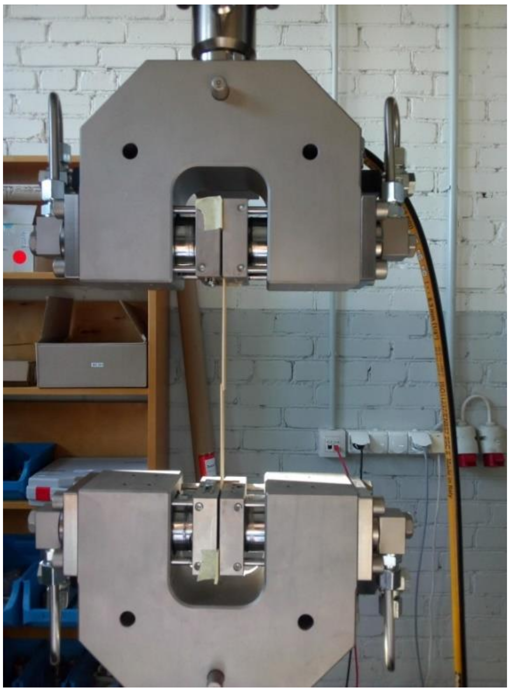
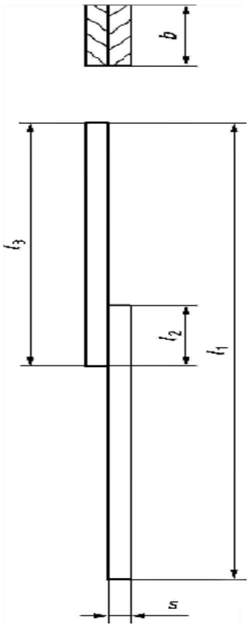


Figure 3.5.3. 1 Bonding quality test specimen and Zwick/Roell Z050 machine



Here,

l1 is the length of test piece (235 ± 2) mm

b is width of test piece (20 ± 0.2) mm

l3 is length of test slip (120 ± 2) mm

s is the thickness of test slip (1.0; 1.5;2.6;3.0) ± 0.1 mm

l2 is length of overlap (5 ± 0.2) mm

Figure 3.5.3. 2 Single lap joint test piece

The bond strength by lap shear test was calculated automatically by the incorporated software of the Universal testing machine Zwick/Roell Z050. Moreover, this bond strength was expressed in Newton per mm^2 (N/mm^2) using the following equation,

$$T = \frac{Fmax}{l_2 x b} = \frac{Fmax}{A}$$

T, Bond Strength
Fmax, is the applied maximum force in Newton (N)
A, is the bonded test surface in square millimetres (mm^2)
l2, is the length of bonded test surface area in millimetres (mm)
b, is the width of the bonded test surface in millimetres (mm)

3.6 Statistical Analysis

Data obtained during this research were statistically analysed by employing Microsoft excel spreadsheet software 365. Single-factor ANOVA analysis of variance (95% confidence interval) was applied followed by Tukey-Kramer Post Hoc Test ($p < 0.05$) to analyse the difference in bond strength of different groups, and difference in surface roughness among wood species and veneer thicknesses. The correlation between veneer surface roughness and bond strength was analysed with the leaner regression analysis method.

4 RESULTS AND ANALYSIS

4.1 Surface Roughness

In appendix 2, mean surface roughness parameter Ra, Rq, and Rz among four species is shown. This table also contains difference in roughness based on the location of samples within a log and based on the thickness of veneer samples. Furthermore, Figure 4.1.1; Figure 4.1.2 and Figure 4.1.3 display the mean roughness profiles Ra, Rq and Rz respectively based on thicknesses for four species.

The lowest roughness in all roughness parameters (Ra, Rq and Rz) were observed on the Black Alder samples, where highest roughness profiles were measured in Aspen. Birch has roughness almost similar to Black Alder, while Grey Alder has a bit higher roughness compared to Birch and Black Alder. ANOVA single factor followed by Tukey-Kramer Post Hoc Test shows that, there are significant differences among the mean roughness in roughness parameters (Ra and Rq) of different species except Black Alder and Birch. However, between Black Alder and Birch, the Rz value is significantly different (Figure 4.1.3). Moreover, between Birch and Grey Alder, Tukey-Kramer Post Hoc Test shows that, there is no significant difference in mean of Rz value for 1.5 mm and 3.0 mm thick samples, but mean Rz of 1.0 mm specimens are different (Figure 4.1.3).

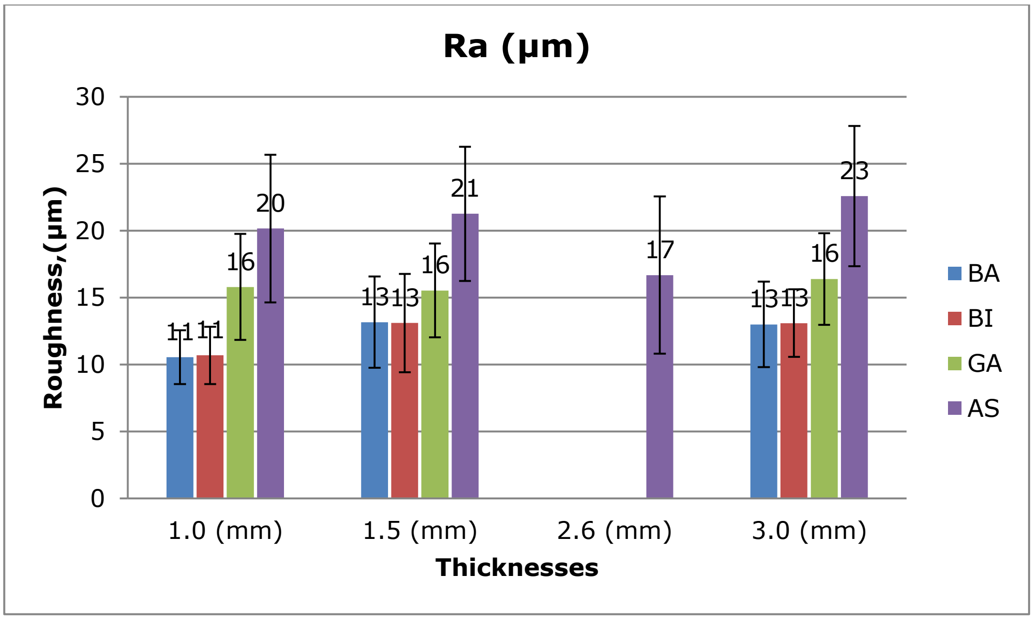


Figure 4.1. 1 Ra Value of Four Species among thicknesses (BA- black Alder, BI- Birch, GA- grey alder, AS- aspen)

However, based on the specimen thicknesses, more significant differences or similarities were observed. In case of Black Alder, Figure 4.1.1, Figure 4.1.2, and Figure 4.1.3 show that, the specimens from 1.0 mm thick veneer have significantly different Ra, Rq and Rz value than the samples from 1.5 mm and 3.0 mm thick veneer, but between 1.5 mm and 3.0 mm thick veneer, there are no significant differences. However, the lowest mean of Ra, Rq and Rz were measured for 1.0 mm thickness. An increment in roughness in all parameter was observed from 1.0 mm to 1.5 mm thicknesses; however, so significant increment in roughness was determined between 1.5 mm to 3.0 mm thicknesses. Rather, from Tukey-Kramer Post Hoc Test it has been found that, Black Alder 1.5 mm thick specimen has a bit higher Ra and Rq value, but lower Rz value compared to 3.0 mm specimens.

Moreover, based on the samples location within the log, for 1.0 mm and 3.0 mm, samples from middle of the log have lowest roughness and samples from bark side of the log have highest roughness. However, 1.5 mm samples showed lowest roughness for samples from bark side of the log and highest roughness for samples from pith side of the log. Moreover, lowest roughness was found in samples from middle of the log of 1.0 mm thick specimen with average Ra 9.8 µm, while samples from bark side of the log of 3.0 mm have highest with average Ra 15.1 µm (Appendix 2).

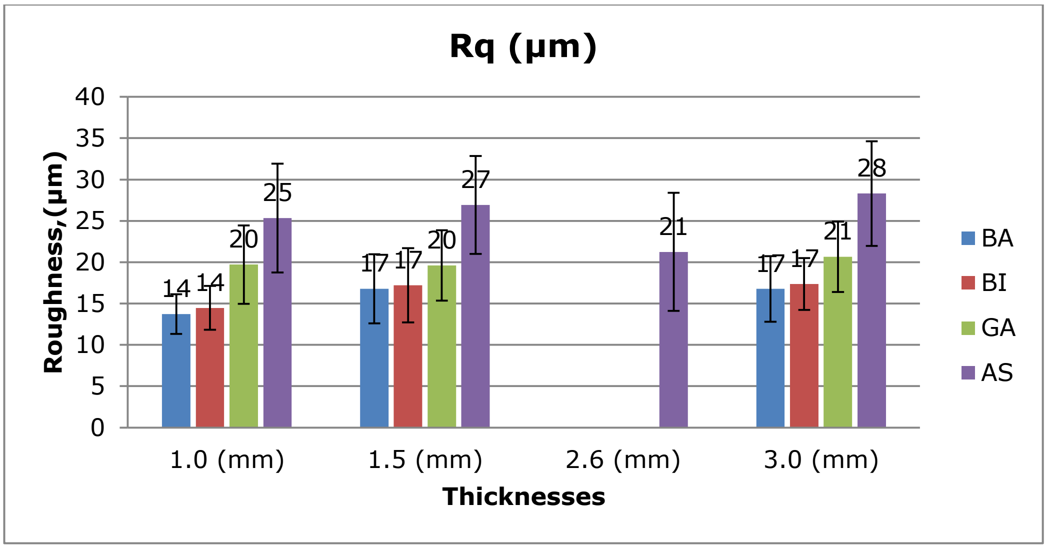


Figure 4.1. 2 Rq Value of Four Species among thicknesses (BA- black Alder, BI- Birch, GA- grey alder, AS- aspen)

Birch showed almost similar types of roughness pattern like Black Alder. Form 1.0 mm to 1.5 mm thickness, there is a significant increment in Ra, Rq and Rz value, but no significant increment from 1.5 mm to 3.0 mm thickness, rather a bidirectional result like Black Alder was observed. Though the mean Ra, Rq and Rz value is not significantly different between 1.5 mm and 3.0 mm thick samples observed from Tukey-Kramer Post Hoc Test, but higher mean Ra value and lower mean Rq and Rz value were observed in 1.5 mm Birch specimen compared to 3.0 mm thick specimen. However, Birch 1.0 mm thick specimen have lowest roughness with having average Ra 10.68 μm; Rq 14.47 μm and Rz 85.75 μm which is significantly different from the average Ra, Rq and Rz value of 1.5 mm and 3.0 mm thick specimens (Figure 4.1.1, Figure 4.1.2, and Figure 4.1.3).

However, based on the samples location within the log, samples from the bark side of the log of 1.0 mm thickness have lowest average Ra. Rq and Rz followed by the middle and pith side samples. While, for 1.5 mm thickness, samples from middle of the log have lowest roughness followed by pith side and bark side samples, and for 3.0 mm thickness, samples from pith side have lowest roughness followed by middle and bark side samples (Appendix 2).

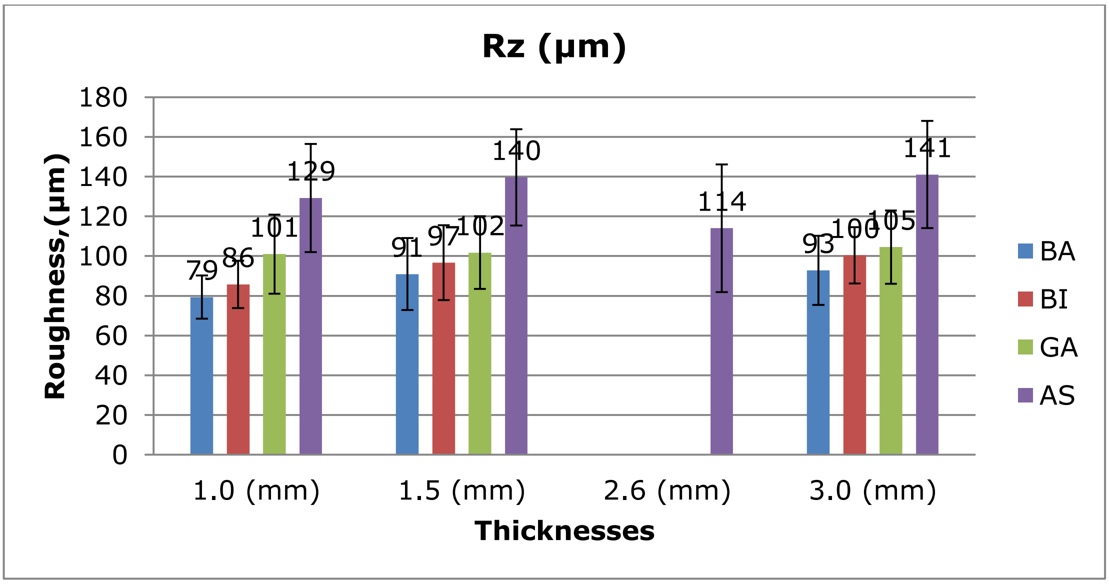


Figure 4.1. 3 Rz Value of Four Species among thicknesses (BA- black Alder, BI- Birch, GA- grey alder, AS- aspen)

For Aspen, dissimilar roughness profiles among thicknesses were observed. Unlike other species, specimens from 2.6 mm Aspen have the lowest roughness compared to the 1.0 mm, 1.5 mm and 3.0 mm thick specimens. Furthermore, Tukey-Kramer Post Hoc Test confirms that for 2.6 mm specimens with average Ra 16.68 μm, Rq 21.25 μm and Rz 114.01 μm are significantly lower than the roughness profiles of other thicknesses. However, highest roughness profiles were measured for 3.0 mm specimens which showed significantly different Ra, Rq and Rz values than 1.0 mm and 1.5 mm specimens in all toughness parameters.

Furthermore, based on the samples location within the log, 1.0 mm specimens from middle of the log have lowest roughness, while 1.5 mm and 2.6 mm from pith side have lowest roughness followed by specimens from bark side and the middle of the log. While, the bark side samples of 3.0 mm thickness have lowest roughness (Appendix 2).

Grey Alder having Ra 15.79 µm for 1.0 mm, 15.54 µm for 1.5 mm and 16.39 µm for 3.0 mm thicknesses (Figure 4.1. 1) indicates that a very little increment in roughness profiles when thickness increased either proportionally or disproportionally. Furthermore, the difference in the average Ra, Rq and Rz among thicknesses for Grey Alder was indicated as not significantly different by ANOVA single factor analysis as well as Tukey-Kramer Post Hoc Test. However, the lowest average Ra and Rq was observed for 1.5 mm thick specimens and lowest average Rz for 1.0 mm thick specimens, while highest roughness profiles were observed for 3.0 mm thick specimens.

Regarding samples location within the log, the highest roughness value were observed for samples from middle of the log of 3.0 mm thickness having Ra 17.5 µm, Rq 22 µm and Rz 110.4 µm, and the lowest roughness value were observed for samples from middle of the log of 1.0 mm thickness with Ra 14.3 µm, Rq 18 µm and Rz 95.1 µm. As for 1.5 mm specimens, Bark side specimens have lowest roughness profiles compared to the specimens from middle or pith side of the log (Appendix 2).

4.2 Bond Strength Based on Species

The bond strength results of Aspen 2.6 mm specimen were taken into the consideration to find out the difference in mean in general, during the analysis of bond strength based on species. However, they were not considered when the analysis was done further deeper, only within a specific groups of observations as the results of other species for 2.6 mm thickness were not available to make comparison. Figure 4.2.1, Figure 4.2.2, and Figure 4.2.3 display the mean bond strength among species and Figure 4.2.4 shows the distribution of bond strength based on species.

However, in general, Tukey-Kramer Post Hoc Test indicates that, there are no significant difference in bond strength among species Black Alder, Grey Alder, and Aspen. However, Birch has significantly higher bond strength than other three species.

However, bond strengths with different species were further analysed within a selected group based on thickness of samples and types of adhesives, where the observed results were found different than the initial results.

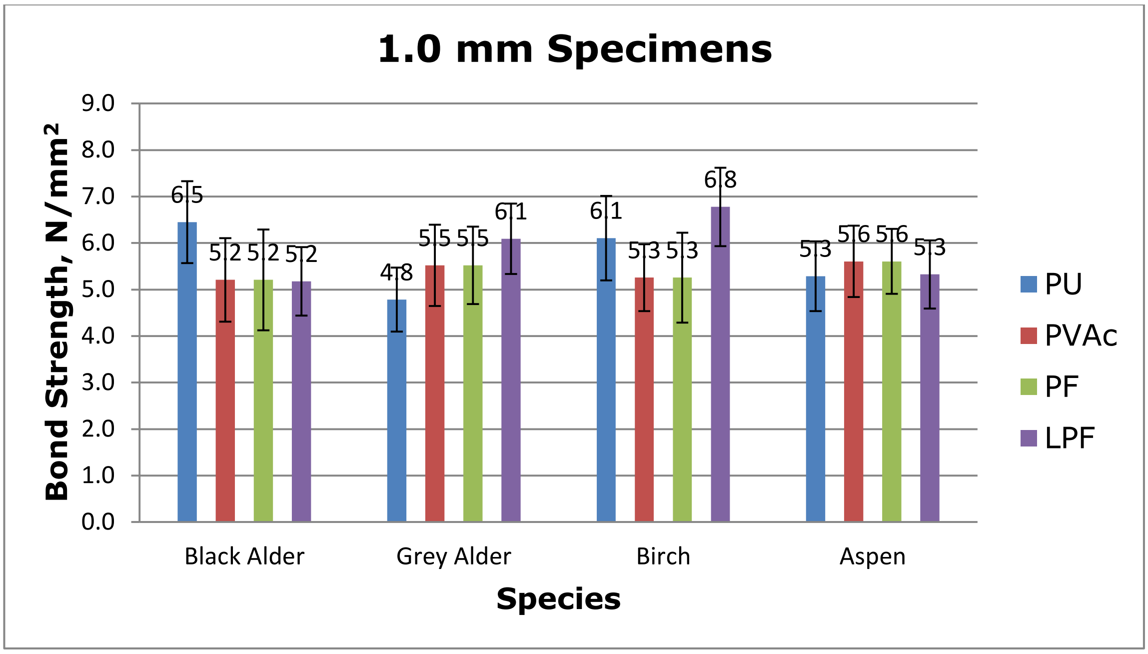


Figure 4.2. 1 Mean bond Strength among Wood Species for 1.0 mm thick Specimens (PU- polyurethane adhesives, PVAc- polyvinyl acetate, PF- phenol formaldehyde, LPF- lignin-based phenol-formaldehyde)

Considering thickness and adhesives, species showed irregular pattern in bond strength. For instance, between Black alder and Grey alder, there are significant difference observed in ANOVA single factor and Tukey-Kramer Post Hoc Test analysis for the bond strength of Black Alder and Grey Alder with 1.0 mm thickness and PU, LPF adhesive and with 1.5 mm thickness and PVAc (Figure 4.2.1). However, the analysis with other thickness and adhesive combinations for these two species did not show any significant difference. Furthermore, with 1.0 mm thickness and PU, Grey Alder had the lowest bond strength of 4.78 N/mm^2 among the species.

In case of Black Alder and Birch, though initial analysis showed that, there is significant difference in bond strength between them, but considering thickness and adhesives the only significant difference was found between them with 1.0 mm thickness (Figure 4.2.1) and LPF and with 3.0 mm thickness and PF (Figure 4.2.3), while in other cases, no significant difference in bond strength between them were found. For Birch, the highest bond strength of 11.70 N/mm^2 was found with 3.0 mm thickness and LPF and the lowest bond strength of 5.26 N/mm^2 was found with 1.0 mm thickness and PVAc. Same types of results with irregular pattern were also observed between Black Alder and Aspen. Based on tukey-Kramer Post Hoc test analysis, in some cases, the bond strengths are significantly different and in some cases they are not. Between Black alder and Aspen, the Black alder with 1.0 mm thickness and LPF have the lowest bond strength of 5.18 N/mm^2, while Aspen with 3.0 mm thickness and LPF have highest mean bond strength of 10.29 N/mm^2 (Figure 4.2.3).

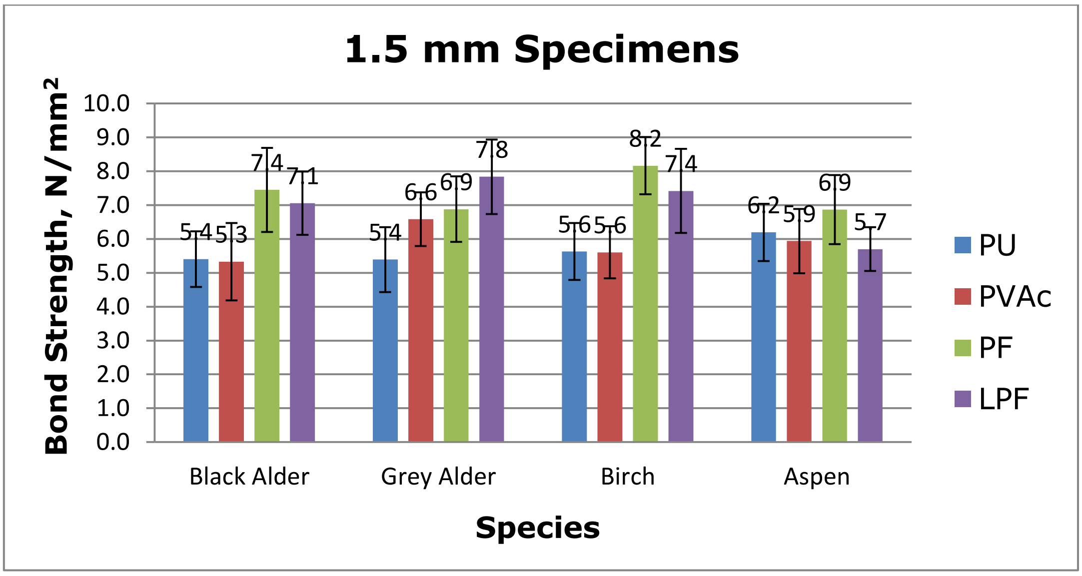


Figure 4.2. 2 Mean bond Strength among Wood Species for 1.5 mm thick Specimens (PU- polyurethane adhesives, PVAc- polyvinyl acetate, PF- phenol formaldehyde, LPF- lignin-based phenol-formaldehyde)

However, between Grey Alder and Birch, significant differences in bond strength were observed for 1.0 mm thickness with PU adhesive having 4.78 N/mm^2 for Grey alder and 6.11 N/mm^2 for Birch (Figure 4.2.1), and specimens of 1.5 mm thickness with PF having bond strength of 6.87 N/mm^2 and 8.16 N/mm^2 for Grey alder and Birch respectively (Figure 4.2.2). In other combinations, no differences were observed between these two species.

Furthermore, between Grey alder and Aspen in few analyses they showed similarities in bond strength and in few cases there are significant differences between them. However, the largest difference in bond strength between them was found for thickness 3.0 mm and PF, where Grey Alder has bond strength of 8.44 N/mm^2 and Aspen has 10.29 N/mm^2. Moreover, with bond strength of 6.88 N/mm^2 and 6.87 N/mm^2 for Grey Alder and Aspen respectively was the minimum difference in bond strength observed between them for thickness 1.5 mm and PF.

Figure 4.2. 3 Mean bond Strength among Wood Species 3.0 mm thick Specimens (PU-polyurethane adhesives, PVAc- polyvinyl acetate, PF- phenol formaldehyde, LPF-lignin-based phenol-formaldehyde)

Furthermore, between Aspen and Birch, both similarity and variation were observed in obtained bond strength. Some cases, Aspen has higher bond strength up to 20% approximately than Birch. While in other observations, Birch showed higher bond strength than Aspen up to 19% approximately. However, the lowest differences among species in bond strength were observed for thickness 1.0 mm and PVAc. Moreover, with PF and 3.0 mm thickness (Figure 4.2.3), the highest significant difference in bond strength were observed, while Black Alder, Grey alder, Birch and Aspen have bond strength of 8.81 N/mm^2, 8.45 N/mm^2, 11.70 N/mm^2, 10.29 N/mm^2 respectively.

Furthermore, Figure 4.2.4 also shows that, lowest bond strength was observed with Grey alder species, where highest bond strength was found with Birch. Moreover, all four species have quite big differences in bond strength between the lowest and height value, such as for Birch; the lowest bond strength is 5.25 N/mm^2, while height bond strength is 11.70 N/mm^2. However, most frequencies of Birch were observed in between 7-8 N/mm^2. Aspen also showed similar results like Birch. Grey alder also has significant differences between height and lowest value and the most frequencies were observed around 7 N/mm^2. In case of Black Alder, which has lowest differences between highest and lowest bond strength compared to other three species and most frequencies were observed between 6-8 N/mm^2.

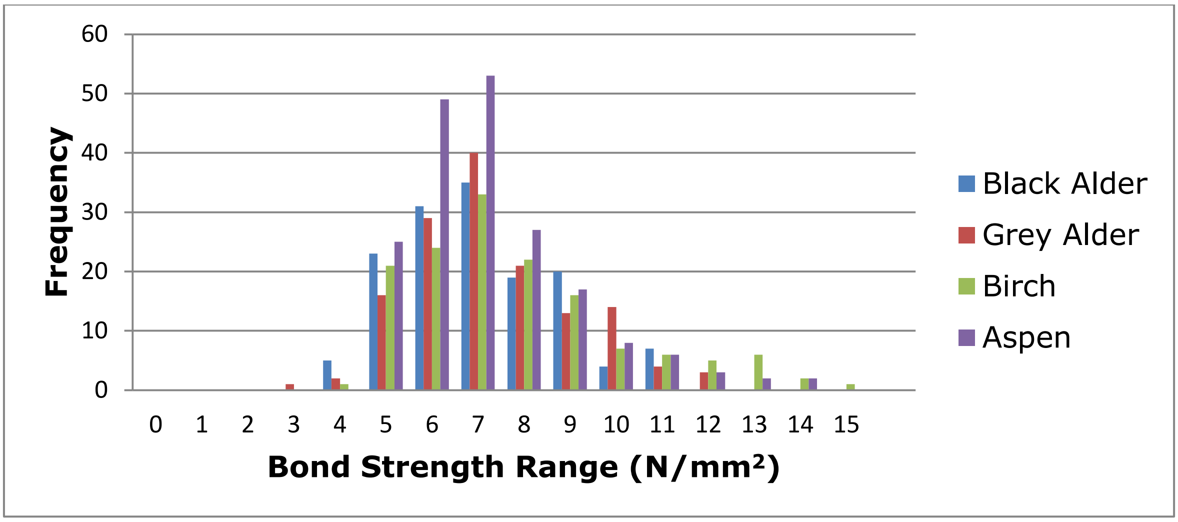


Figure 4.2. 4 Bond Strength Distribution based on Species

4.3 Relation among veneer thickness, roughness and adhesives with bond strength

Noticeably significant different bond strengths were observed based on the veneer thickness and roughness. A successive increase was observed in mean bond strength from 1.0 mm thick veneer to 3.0 mm thick veneer (Figure 4.3.1). Tukey-Kramer Post Hoc Test also indicates that, there are significant differences in mean bond strength among thickness except between 2.6 mm and 3.0 mm. In general, the height bond strength was measured for 3.0 mm thickness and lowest was measured for 1.0 mm thickness. Furthermore, based on the adhesives, significant differences in mean bond strength among adhesives were observed except between PU and PVAc (Figure 4.3.2). PU has the lowest average mean bond strength with 5.84 N/mm^2, followed by PVAc with 6.28 N/mm^2 and LPF 7.23 N/mm^2, finally by PF with height average bond strength of 8.02 N/mm^2.

Though, a successive increment among mean bond strength based on thickness and significant differences based on adhesives were measured, but analysis with smaller group based on thicknesses and adhesives, also considering species showed some deviation in this successive increment or different results.

Black alder showed significant variation in bond strength among thickness and adhesives. Figure 4.3.1 shows the average bond strength based on thicknesses and adhesives. 1.0 mm thick specimen of Black alder, which have the lowest surface roughness compared to 1.5 and 3.0 mm thick specimens, have highest average bond strength of 6.7 N/mm^2 with PF adhesive, followed by PU with 6.5 N/mm^2. The lowest average bond strength for 1.0 mm thickness was found with PVAc and LPF.

ANOVA single factor and Tukey-Kramer Post Hoc Test indicated that, there are significant differences in mean bond strength among adhesives except PVAc and LPF for 1.0 mm thick specimen. Specimen with 1.5 mm thickness, have lower average bond strength than 1.0 mm specimen only with PU, similar strength with PVAc, but very high average bond strength with PF (approximately 10% higher) and LPF (approximately 35% higher). Though, the Specimen with 1.5 mm thickness have higher surface roughness, yet they showed better average bond strength than 1.0 mm thick specimen. However, PF provides the highest average bond strength of 7.4 N/mm^2 for specimen with 1.5 mm thickness and the lowest strength was observed with PVAc 5.3 N/mm^2.

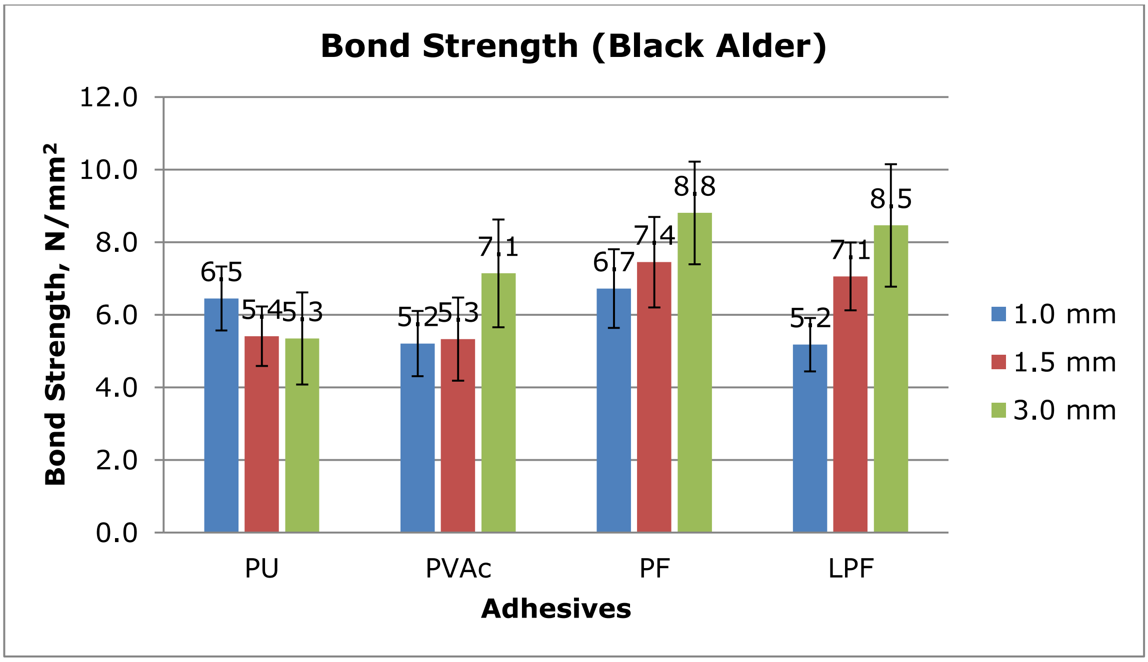


Figure 4.3. 1 Mean bond strength based on thicknesses and adhesives for Black Alder (PU- polyurethane adhesives, PVAc- polyvinyl acetate, PF- phenol formaldehyde, LPF- lignin-based phenol-formaldehyde)

However, the specimen with 3.0 mm thickness, have the lowest bond strength of 5.3 N/mm^2 with PU and highest bond strength of 8.8 N/mm^2 with PF. For the specimen with 3.0 mm thickness, significant differences in average bond strength based on adhesives have been observed. 3.0 mm thick specimen have higher surface roughness profiles compared to 1.0 mm, and almost identical roughness profiles with 1.5 mm specimen, yet 3.0 mm specimen formed better strength with PVAc (approximately 33% higher than other thicknesses), PF (approximately 18% higher than 1.0 mm and

30% higher than 3.0 mm) and LPF (approximately 60% higher than 1.0 mm and 20% higher than 3.0 mm), but lower strength with PU (approximately 20% lower than 1.0 mm) than other thicknesses.

However, PF have higher average bond strength with all thicknesses compared to other adhesives, regardless the roughness profiles of the specimen, while 3.0 mm thick specimen showed higher strength with different adhesives except PU. Apart from PF, LPF formed higher strength with 1.5 mm and 3.0 mm thickness, while PU formed higher strength with 1.0 mm thickness. Furthermore, PVAc formed lowest strength with both 1.0 mm and 1.5 mm thickness.

Grey Alder with almost identical roughness profiles among thicknesses, but higher compared to Black Alder, showed a pattern in average bond strength increment from lowest thickness to highest thickness. Figure 4.3.2 shows the average bond strength based on thicknesses and adhesives for Grey Alder specimen. From the analysis, it has been observed that, when thickness increases bond strength increases with all different adhesives, though the roughness profiles of these thicknesses are identical and differences in these roughness profiles among the thicknesses may be negligible. Highest strength of 6.6 N/mm^2 was formed by 1.0 mm specimen with PF, while with PU, it is 4.8 N/mm^2 and lowest. Moreover, with PVAc the average bond strength of 1.0 mm thick specimen is 5.5 N/mm^2 and 6.1 N/mm^2 with LPF.

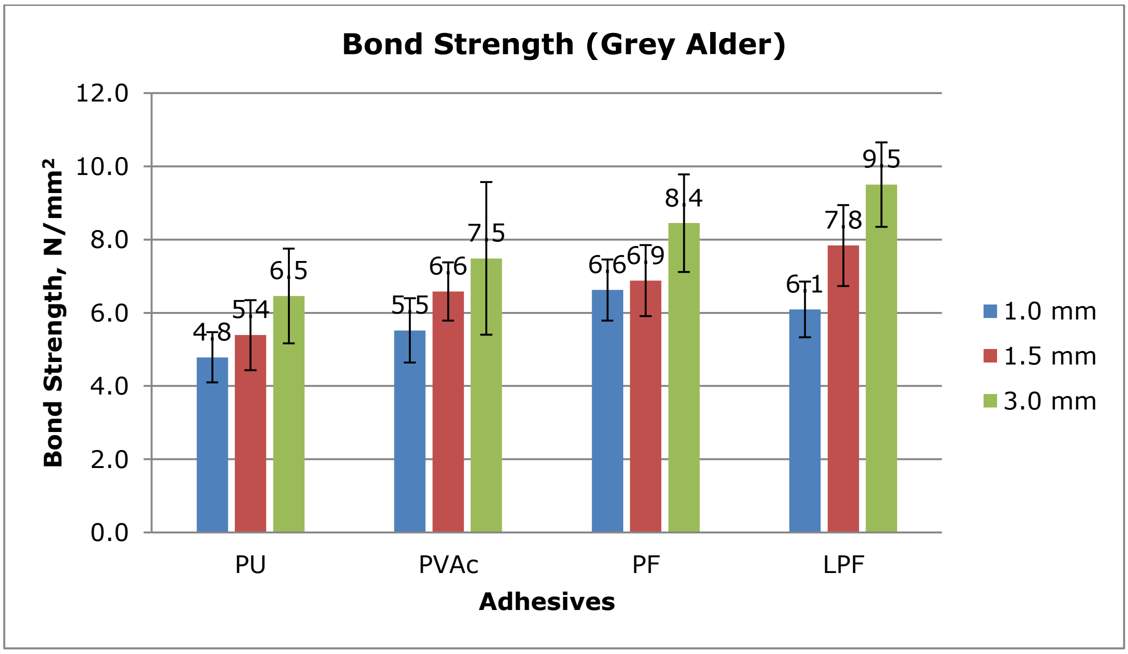


Figure 4.3. 2 Mean Bond strength based on thicknesses and adhesives for Grey Alder (PU- polyurethane adhesives, PVAc- polyvinyl acetate, PF- phenol formaldehyde, LPF- lignin-based phenol-formaldehyde)

However, in case of 1.5 mm thick specimen, the average bond strength increases significantly compared to the strength of 1.0 mm thick specimen, and the percentage of the increment is approximately 12% with PU, 20% with PVAc, 5% with PF and the highest of 27% with LPF. Moreover, the average bond strength with 3.0 mm thickness, much more significant differences were observed with 1.0 mm and 1.5 mm thicknesses. Specimen with 3.0 mm thickness of Grey Alder, formed significantly higher bond strength with all adhesives compared to 1.0 mm and 1.5 mm thick specimen. The average bond strengths of 3.0 mm thick specimen are approximately 15% to 25% higher than 1.5 mm thick specimen and 30% to 60% higher than 1.0 mm thick specimen with different adhesives. However, the highest average bond strength of 9.5 N/mm^2 was observed with LPF and 3.0 mm thickness and the lowest of 4.8 N/mm^2 with PU and 1.0 mm thickness.

Furthermore, significant differences were observed on average bond strength based on adhesives. PU provided the lowest strengths having 4.8 N/mm^2 with 1.0mm, 5.4 N/mm^2 with 1.5 mm and 6.5 N/mm^2 with 3.0 mm thickness compared to other adhesives, while PVAc has significantly higher strength compared to PU. PF with 6.6 N/mm^2 with 1.0mm, 6.9 N/mm^2 with 1.5 mm and 8.4 N/mm^2 with 3.0 mm thickness, showed significantly higher strength than PU and significantly higher strengths in case of 1.0 mm and 3.0 mm thicknesses than PVAc. While with Grey Alder, highest mean bond strength was formed by LPF with 1.5 mm and 3.0 mm thickness than PU, PVAc and PF, but lower strength with 1.0 mm thickness than PF. However, specimens with different thicknesses of Grey Alder have identical roughness profiles, yet with combination of adhesives and thicknesses they provide significantly different results.

Birch, in case of Birch almost identical results were observed like Grey Alder and Black Alder in terms of increment in bond strength when thickness increases, except one variation with PU, where 1.0 mm thick specimen have higher strength of 6.1 N/mm^2 and the lowest of 5.4 N/mm^2 was measured with 3.0 mm thickness. This variation is further identical to the Black Alder specimen strengths with PU. However, with other adhesives the increments in bond strengths are significantly higher among thicknesses. PVAc has strength of 5.3 N/mm^2 with 1.0 mm, 5.6 N/mm^2 with 1.5 mm and significantly higher strength of 8.4 N/mm^2 with 3.0 mm thickness. The average strength between 1.0 mm and 1.5 mm is not significantly different, but the average strength of PVAc with 3.0 mm thickness is approximately 50% higher than 1.0 mm and 1.5 mm thickness. Figure 4.3.3 shows the average bond strength based on thicknesses and adhesives for Birch specimen.

While, with PF, 1.0 mm thick specimen have average strength of 6.9 N/mm^2 which is the lowest and approximately 16% lower than the average strength of 1.5 mm thick specimen and approximately 70% lower than the average strength of 3.0 mm thick specimen. While, the difference between 1.5 mm and 3.0 mm is also significant with 8.2 N/mm^2 and 11.7 N/mm^2 for 1.5 mm and 3.0 mm thickness respectively. LPF also showed similar results like PF, having average bond strength of 9.8 N/mm^2 for 3.0 mm thick specimen which is approximately 32% higher than 1.5 mm thick specimen and approximately 45% higher than 1.0 mm thick specimen. Furthermore, 1.5 mm thick specimens have average bond strength of 7.4 N/mm^2 which is approximately 10% higher than 1.0 mm thick specimen.

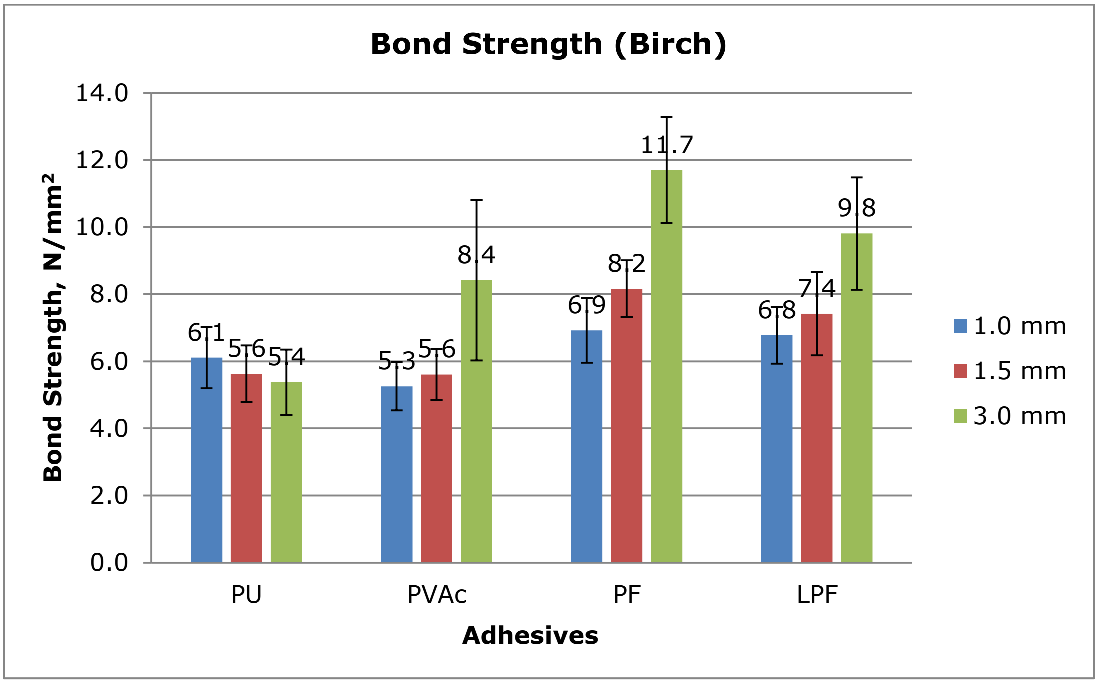


Figure 4.3. 3 Mean Bond strength based on thicknesses and adhesives for Birch (PU- polyurethane adhesives, PVAc- polyvinyl acetate, PF- phenol formaldehyde, LPF-lignin-based phenol-formaldehyde)

However, with Birch specimen, the better bond strengths were observed with PF, followed by LPF, and comparatively lower bond strengths were measured with PU. PU has mean bond strength of 6.1 N/mm^2 with 1.0 mm thickness, and analysis indicated that, this mean bond strength is significantly higher than the mean bond strength measured with PVAc, but significantly lower than the mean bond strengths measured with PF and LPF with 1.0 mm thick specimen. However, with 1.5 mm thick specimen, the mean bond strengths with PU and PVAc were identical, but significantly lower than, PF and LPF. However, in case of 3.0 mm thick specimen, PF, LPF and PVAc have significantly higher strengths and among PF has higher value with 11.7 N/mm^2 which is approximately 40% higher than PVAc and approximately 20% higher than LPF. Overall, PF have higher bond strength with Birch and 3.0 mm thick specimen also showed higher results except with PU.

Furthermore, 1.0 mm thick specimens of Birch have lowest surface roughness, while 1.5 mm and 3.0 mm thick specimen have identical surface profiles between them, but higher than 1.0mm thick specimen, which is indistinguishable with specimen of Black Alder roughness. Similar to Black Alder, in case of birch, only with PU the mean bond strength decreases when surface roughness increases. However, with other adhesive, the findings were opposite, when roughness increases bond strength also increases. However, as mentioned above, that the roughness profiles of 1.5 mm and 3.0 mm thick specimen of Birch are identical, yet these thicknesses showed significantly different mean bond strength with higher percentage of variation with different adhesives.

Aspen, Figure 4.3.4 shows the average bond strength based on thicknesses and adhesives for aspen specimen. Unlike other species, 2.6 mm thick specimens were available for aspen. However, the lowest mean bond strengths were observed with 1.0 mm thick specimen of Aspen, which is significantly lower than other thicknesses. While, mean bond strengths measured in 1.5 mm specimens were approximately 5% to 25% higher than mean bond strengths of 1.0 mm thick specimens, and approximately 10% to 43% and approximately 10% to 50% lower than mean bond strengths of 2.6 mm and 3.0 mm specimens respectively. Furthermore, between 2.6 mm and 3.0 mm thick specimens, 2.6 mm specimens have higher bond strength than 3.0 mm specimens with PU, but not significantly higher.

Moreover, with PVAc, 2.6 mm specimens have significantly higher bond strength than 3.0 mm specimens. However, with PF and LPF the results were opposite; 3.0 mm thick specimens have approximately 5% and 17% higher mean bond strength than 2.6 mm specimens respectively. Moreover, highest bond strength was observed by 3.0 mm thick specimens and lowest was found with 1.0 mm thick specimen with PU and LPF. Figure 4.3.4 shows the average bond strength based on thicknesses and adhesives for Birch specimen.

Higher average bond strengths were observed with PF, except for 1.0 mm thick specimen, where PVAc has higher bond strength with 5.6 N/mm^2, though the bond strengths among adhesives with 1.0 mm thick specimens are almost identical. In case of 1.5 mm thick specimens, PF has significantly higher mean bond strength of 6.9

N/mm^2 than other adhesives, while lowest was observed with LPF having 5.7 N/mm^2. However, with 2.6 mm and 3.0 mm thick specimens, PF formed far higher and significantly different bond strength compared to other adhesives. Such as, PF has bond strength of 10.3 N/mm^2 and 9.9 N/mm^2 for 3.0 mm and 2.6 mm thick specimens respectively, while LPF has 8 N/mm^2 and 6.8 N/mm^2 for 3.0 mm and 2.6 mm thick specimens respectively. Furthermore, with PU and PVAc no significant differences were observed between the bond strength of 2.6 mm and 3.0 mm thick specimens.

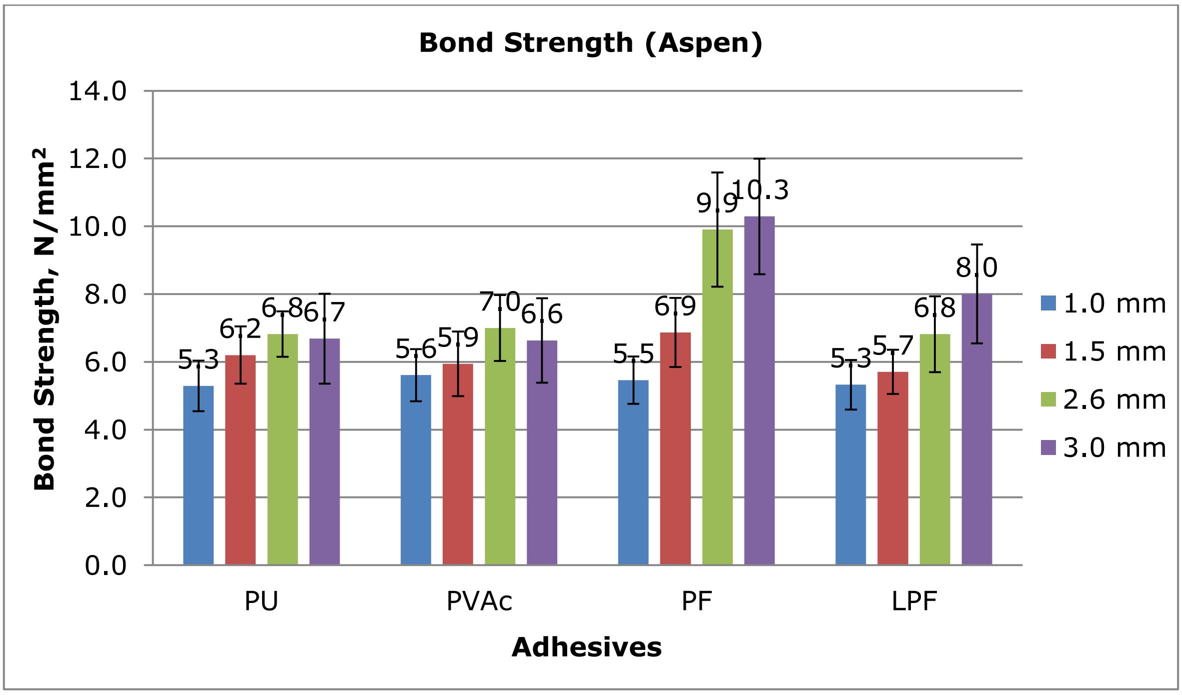


Figure 4.3. 4 Mean Bond strength based on thicknesses and adhesives for Aspen specimen (PU- polyurethane adhesives, PVAc- polyvinyl acetate, PF- phenol formaldehyde, LPF-lignin-based phenol-formaldehyde)

Furthermore, lowest roughness profiles measured with 2.6 mm thick specimens of Aspen having Ra of 17 µm, Rq of 21 µm and Rz of 114 µm, which are significantly lower compared to other thicknesses of Aspen, but quite identical to the roughness of 3.0 mm thick specimens of other species and in few cases with 1.5 mm thick specimens of other species. However, bond strengths of 2.6 mm thick aspen specimens are quite identical to other species, such as with PVAc, 2.6 mm thick aspen specimens have mean bond strength of 7.0 N/mm^2, while for Black Alder it is 7.1 N/mm^2 with 3.0 mm thick specimens, which indicates the similar types of results with similar roughness profiles regardless the thickness.

However, specimens of Aspen with other thicknesses have greater roughness profiles than other species and among the thicknesses, 1.0 mm thick specimens have lower and 3.0 mm thick specimens have higher roughness profiles. However, the differences among 1.0 mm, 1.5 mm and 3.0 mm thick specimens are not significant except 1.0mm to 3.0 mm. However, like other species, it has been observed that, 1.5 mm thick specimens with higher roughness profiles than 1.0 mm thick specimen have better bond strength, while 3.0 mm thick specimens have significantly higher bond strengths compared to the 1.0mm and 1.5 mm thick specimens, though 3.0 mm thick specimens have highest roughness profiles.

Furthermore, an attempt was taken to find out if there are any correlations between surface roughness of specimens and bond strength provided. This correlation was observed by measuring Pearson correlation coefficient with regression model in Microsoft Excel Spreadsheet Software 365 as well as applying the Relationship Rules of Thumb. Data were separated in to 52 groups according to their species, veneer thickness and applied adhesives and then the regression model was applied to each group separately to determine whether there are any correlations between surface roughness's of specimens or not.

However, out of 52 groups, only three groups showed that, there is a positive correlation between surface roughness of specimens and bond strength. Aspen 1.0mm and 1.5 mm thick specimen with PU, and Aspen 2.6 mm thick specimen with LPF showed correlation between surface roughness of specimens and bond strength. However, in case of the other 49 groups, Pearson's coefficient *r,* were found near to zero indicating no linear relationship, P-value also indicated that no correlation exists. Relationship Rules of Thumb measurement also confirmed that, no correlation between surface roughness of specimens and bond strength.

5 DISCUSSION

Several studies show that, the roughness of veneer increases when thickness of veneer increases (Bekhta et al., 2020; Daoui et al., 2011; Dundar et al., 2008). However, in this research both similar and different types of results were found. Roughness profiles always do not increase when thickness increased. In this research, in few cases it has been measured that, thicker veneers have lower roughness profiles that thinner veneers. These examples are, such as 3.0 mm Black Alder Veneers have lower roughness profiles than 1.5 mm Black Alder veneers, then 2.6 mm Aspen veneers have lower roughness profiles than 1.0 mm and 1.5 mm veneers, 1.5 mm Grey Alder Veneers have lower roughness profiles than 1.0 mm Grey Alder veneers. Furthermore, Birch 1.5 and 3.0 mm veneers have identical roughness profiles.

However, 2.6 mm aspen specimens showed significantly lower roughness profiles than 1.0 mm and 1.5 mm aspen specimens; this might result from the maintenance of Lathe Raute 3HV66 machine, and application of an entirely new peeling blade for 2.6 mm aspen specimens. Moreover, no patterns were observed in roughness profiles based on the samples location within the log. Different species provide different types of results for bark side, pith side specimens and specimens from middle of the log.

Several studies showed that, bond strength decreases when veneer thickness increases, due to the formation of lathe checks in thicker veneer (Khoo et al., 2019); due to the less specific gravity of LVL or plywood produced with thicker veneer (Daoui et al., 2011; De Melo and Del Menezzi, 2014) as well as due to the large number of pores and void volume in thick veneer compared to thin veneer (Vick, 1999). However, in this research most of the cases; it has been observed that, bond strength increased when thickness of veneer increased except few such as PU formed higher bond strength with 1.0 mm thick Black Alder and Birch specimens, but lower strength with 1.5 mm and 3.0 mm thick Black Alder and Birch specimens. Moreover, 2.6 mm thick Aspen veneer showed higher bond strength with PU and PVAc compared to 3.0 mm thick aspen veneer.

However, in this research, it has been observed that bond strength increases with the increment of thicknesses, which partially disagrees with the findings of others. However, this variation in finding may be explainable when considering the direction of specimens in the lap-shear test. In the lap shear test, the specimen direction is different than plywood or LVL, and due to that, the effects of lathe checks were not remarkable. The observed results were not correlated with the products (Plywood, LVL) test results. Furthermore, in the previous studies, it was not commonly discussed how their checks affected the results and what were the checks properties. Thus, this might be an area to investigate further.

Furthermore, during this research, the author's observation about pre-load provided by the clamps of universal testing machine Zwick/Roell Z050 might influence a certain degree to the bond strength. When a specimen is attached to the clamps of the Zwick/Roell machine, it applies a pre-load (either tension or compression) to the specimen due to the hydraulic force used by these clamps. However, when it provides compression force, the thinner veneer tends to bend to a certain degree or vibrate for a moment as both ends of the specimen are attached firmly with the clamps.

Moreover, during this occurrence, the most affected area of the specimen is the bond area. During this research work, few samples of 1.0 mm thickness were broken within the bond area during this sample loading stage. Samples with less physical strength might get affected more during this sample loading stage than the samples with better physical strength. However, this occurrence might be a minor reason that thinner veneer specimens have lower bond strength than thicker veneer, as thinner veneer specimens have less physical strength than thicker veneer specimens.

Furthermore, lowest bond strengths were observed with 1.0 mm thick veneers compared to other thicknesses, though 1.0 mm thick veneers has relatively low roughness profiles. Moreover, the specimens with other thicknesses showed higher bond strength though they have higher roughness profiles compared to 1.0 mm specimen. This finding agreed with the findings of other researcher, such as Gent and Lai, (1995), who stated that bonding improved with the roughening of a surface, and with Packham, (2003) who remarked that, adhesives prefer porous surface over the smooth surface to form a strong bond.

However, this finding disagrees with other researchers and their observations, which is, if surface roughness is too high then it resulted in poor quality bonding (Aydin, 2004; DeVallanc et al., 2007; Follrich et al., 2010; Marra, 1992). However, the measured variation from these researchers may be subjected to the range of the roughness profiles of specimens used in this research. Specimens were prepared from the best veneer sheets available and from more homogenous and finest area of the veneer sheets. Consequently, specimens might have the roughness profiles within the most suitable ranges for better bond. Thus, almost no decline of bond strength observed due to the increment of roughness of specimens.

Furthermore, based on adhesives, PF has the highest bond strength, while PU has the lowest. PU is isocyanate adhesives, and requires higher moisture content for better performance with wood. However, specimens used in this research have moisture content of approximately 3-6%, means not sufficient number of hydroxyl groups are present in the specimens for isocyanate to react and deliver better bond. PVAc showed higher bond strength than PU but lower than LPF and PF. PVAc normally flow smoothly into the exposed cell lumen, but due to its higher molecular weight and viscosity, the penetration rate of PVAc into cell wall is considerably low for better bond. Moreover, PVAc tends to creep under pressure. For these reasons, PVAc might have showed lower bond strength than LPF and PF.

Furthermore, PF showed higher bond strength than other adhesives. This finding is may be due to the higher penetration rate of PF into wood cell wall and reaction with lignin. PF can penetrate to the cell wall microvoids (Rittiphet et al., 2021) and formaldehyde reacts with lignin to form methylolated lignin, resulting better performance in bonding by PF with wood. Moreover, LPF has properties similar to PF resin, but LPF reactivity is too low compared to PF. Moreover, LPF has higher viscosity and low level of substitution of cell wall molecule. These properties of LPF justify that LPF has lower bond strength than PF resin.

6 CONCLUSION

This research aimed to evaluate the effect of different factors such as wood species, veneer thickness and surface roughness, and adhesives on lap shear bond strength. Four different wood species (Black Alder, Grey Alder, Birch, and Aspen) were used to manufacture veneers with different thicknesses and specimens, and four different adhesives (PU, PVAc, PF, and LPF) were used for bonding. Lap shear tests were conducted by Zwick/Roell Universal testing machine, and the results were analysed by ANOVA single factor followed by Tukey-Kramer Post Hoc Test ($p < 0.05$). Based on the findings during this research, the following conclusion can be made:

1. Roughness profiles of black alder specimens were identical to birch specimens, while grey alder and aspen have significantly higher roughness profiles than black alder and birch. Moreover, between grey alder and aspen, there are significant differences in roughness profiles.
2. The surface roughness of the veneer increases significantly when thickness increases. However, different results were also observed, such as thicker veneer also showed significantly lower or identical roughness compared to thinner veneer.
3. Birch has better and significantly different bond strength in general than Black Alder, Grey Alder, and Aspen, while bond strengths among Black Alder, Grey Alder, and Aspen are not significantly different.
4. Bond strength increases when the thickness of the veneer increases, and the increment in bond strength based on veneer thicknesses is significant.
5. Surface roughness is a minor factor affecting bond strength, and no correlation was observed between the surface roughness of specimens and the bond strengths provided by the specimens; as for lower roughness profiles, both lower and higher bond strengths were observed. Conversely, higher roughness profiles also provided significantly higher and lower bond strengths.
6. PF showed the highest bond strength, and there are significant differences in bond strength among species.

Overall, it seems that the thickness and adhesives are the most significant factors that are affecting the bond strength. However, the bonding strength evaluation is a complex procedure as several factors and procedures from the veneer production stage to the bond strength testing can affect the bond strength.

SUMMARY

Adhesives are widely used raw materials for woodworking technology, and the bonding technology of adhesives is considered a key technology for physically and mechanically stable wood products. However, this bonding technology of adhesives with wood is a complex mechanism and affected by several factors. Thus, this research aims to identify and analyse the effect of factors like species, veneer thickness, surface roughness, and adhesives on adhesive bond strength.

Four hardwood species, black alder, grey alder, European aspen, and silver birch, were used to prepare veneers with four different thicknesses of 1.0 mm, 1.5 mm, 2.6 mm, and 3.0 mm. The samples for bond strength evaluation were made from these veneers, while surface profiles of these samples were measured according to the test standard ISO 4287:1997. Before gluing and pressing operation, the pressing time was determined by combining the time required by different thicknesses to achieve the desired temperature and the curing time for adhesives suggested by the manufacturer. Furthermore, according to manufacturer instructions, the pressing temperature was determined, and the adhesive spread rate was kept constant for all adhesives to analyse their effect on bond strength. Finally, the bond strengths were evaluated by single lap shear testing according to the standard ASTM D7998 – 19 in the controlled laboratory environment.

However, analysis of the results obtained during this study showed that, generally, birch has better (7%-10%) and significantly different bond strength in general than Black Alder, Grey Alder, and Aspen. In contrast, bond strengths among the other three species are quite identical. Moreover, it has been observed that veneer thickness is one of the significant factors affecting the bond strength, and bond strengths increased significantly when veneer thicknesses increased. However, factors like surface roughness showed indecisive behaviour as both lower and higher roughness profiles provided both lower and higher bond strengths. Moreover, no correlation was observed between roughness profiles and bond strength. Furthermore, adhesives showed that they are also significant factors affecting bond strengths. Moreover, among the adhesives, PF showed significantly better bond strength than other adhesives.

Overall, it seems that the thickness and adhesives are the most significant factors affecting the bond strength. However, factors like the anatomical structure of wood,

the effect of certain machining procedures, and adhesive penetration into the wood cell should be further investigated to precisely evaluate the adhesive bond strength.

KOKKUVÕTE

Liimid on puidutöötlemise tehnoloogias laialdaselt kasutatavad toorained ja liimühenduste tehnoloogiat peetakse füüsikaliselt ja mehaaniliselt stabiilsete puittoodete võtmetehnoloogiaks. Puidu liimühenduste tehnoloogia on keeruline mehhanism ja seda mõjutavad mitmed tegurid. Seetõttu on selle lõputöö eesmärgiks välja selgitada ja analüüsida selliste liimühendust mõjutavate tegurite mõju nagu puiduliik, spooni paksus, pinna karedus ja liimid.

Antud töös võrreldi nelja erinevat lehtpuuliiki treispooni valmistamisel: sanglepp, hall lepp, haab, kask. Treispoonid valmistati nelja erinevad paksusega: 1,0 mm, 1,5 mm, 2,6 mm ja 3,0 mm. Nendest spoonidest valmistati liimühenduse katsekehad, milledelt mõõdeti ka pinnakaredused vastavalt standardile ISO 4287:1997. Enne liimühenduste pressimist määrati kindlaks pressimiseaeg erinevatel spoonipaksustel ja erinevate liimidega. Lisaks määrati kindlaks ka pressimise temperatuurid vastavalt liimitootja soovitustele ja liimi pealekandmiskogus hoiti kõigi liimide jaoks konstantsena, et analüüsida erinevate liimide mõju liimühenduse tugevusele. Liimühenduse tugevuste määramisel võeti aluseks standard ASTM D7998-19 ja katsed teostati ülekattega liimliite nihkekatsega.

Antud töö käigus saadud tulemuste analüüs näitas, et kasel on liimühenduse tugevus 7–10% kõrgem ja statistiliselt erinev kui sanglepal, hall-lepal ja haaval. Seevastu teiste kolme lehtpuuliigi liimühendused on omavahel üsna sarnased. Töö käigus täheldati, et spooni paksus on üks olulistest teguritest, mis mõjutab liimühenduse tugevust ning liimühenduse tugevus suurenes märkimisväärselt, kui spooni paksused suurenesid. Samas aga pinnakareduse ja liimühenduse tugevuse vahel selgeid seoseid ei tekkinud ning suuremad ja väiksemad pinnakaredused näitasid mõlemaid suuremaid ja väiksemaid liimühenduse tugevusi. Lisaks ei täheldatud ka karedusprofiilide ja liimühenduse tugevuse vahelist korrelatsiooni. Ka liimid mõjutasid oluliselt liimühenduste tugevust ning PF liim näitas kõikidest teistest liimidest selgelt kõige paremaid liimühenduse tulemusi.

Töögst järeldub, et spooni paksus ja liimid on kõige olulisemad tegurid, mis mõjutavad liimühenduse tugevust. Liimühenduse tugevuse täpseks hindamiseks tuleks veel täiendavalt uurida selliseid tegureid nagu puidu anatoomiline struktuur, teatud töötlemisprotseduuride mõju ja liimi tungimine puidurakku.

REFERENCES

Ansell, M.P., 2015. Wood microstructure-A cellular composite. In: Wood Composites. Elsevier Inc., pp. 3–26.

Aydin, İ., 2004. Activation of wood surfaces for glue bonds by mechanical pre-treatment and its effects on some properties of veneer surfaces and plywood panels. Appl. Surf. Sci. 233, 268–274.

Banks, W., 1995. Advanced wood adhesives technology. Int. J. Adhes. Adhes. 15, 198–199.

Bekhta, P., Salca, E.A., Lunguleasa, A., 2020. Some properties of plywood panels manufactured from combinations of thermally densified and non-densified veneers of different thicknesses in one structure. J. Build. Eng. 29.

Bhat, K., 1980. Variation in structure and selected properties of Finnish birch wood. I. Silva Fenn. 14.

Biziks, V., Bicke, S., Militz, H., 2019. Penetration depth of phenol-formaldehyde (PF) resin into beech wood studied by light microscopy. Wood Sci. Technol. 53, 165–176.

Borůvka, V., Dudík, R., Zeidler, A., Holeček, T., 2019. Influence of site conditions and quality of birch wood on its properties and utilization after heat treatment. Part I-elastic and strength properties, relationship to water and dimensional stability. Forests 10.

Bronia Stefanowski, Spear, M., Pitman, A., 2018. Review of the Use of Pf and Related Resins for Modification of Solid Wood. Timber 2018 165–179.

Browne, F.L., Brouse, D., 1929. Nature of Adhesion between Glue and Wood. Ind. Eng. Chem. 21, 80–84.

Budakci, M., Gurleyen, L., Cinar, H., Korkut, S., 2007. Effect of wood finishing and planing on surface smoothness of finished wood. J. Appl. Sci. 7, 2300–2306.

Cheng, E., Sun, X., 2006. Effects of wood-surface roughness, adhesive viscosity and processing pressure on adhesion strength of protein adhesive. J. Adhes. Sci. Technol. 20, 997–1017.

Claessens, H., Oosterbaan, A., Savill, P., Rondeux, J., 2010. A review of the characteristics of black alder (Alnus glutinosa (L.) Gaertn.) and their implications for silvicultural practices. Forestry 83, 163–175.

Conner, A., 2001. Wood: Adhesives. Encyclopedia of Materials: Science and Technology. Adhes. wood 17.

Daoui, A., Descamps, C., Marchal, R., Zerizer, A., 2011. Influence of veneer quality on beech LVL mechanical properties. Maderas Cienc. y Tecnol. 13, 69–83.

De Melo, R.R., Del Menezzi, C.H.S., 2014. Influence of veneer thickness on the properties of LVL from Paricá (Schizolobium amazonicum) plantation trees. Eur. J. Wood Wood Prod. 72, 191–198.

Debora Grupp AS, 2021. VINEER MÄND MÄNNIVINEERVINEER | MDF | Debora Grupp AS [WWW Document]. URL https://debora.ee/tooted/vineerid/mannivineer/ (accessed 5.1.21).

DeVallanc, D.B., Funck, J.W., Reeb, J.E., 2007. Douglas-fir plywood gluebond quality as influenced by veneer roughness, lathe checks, and annual ring characteristics. For. Prod. J. 57, 21–28.

Dinte, E., Sylvester, B., 2018. Adhesives: Applications and Recent Advances. Appl. Adhes. Bond. Sci. Technol.

Dundar, T., Akbulut, T., Korkut, S., 2008. The effects of some manufacturing factors on surface roughness of sliced Makoré (Tieghemella heckelii Pierre Ex A.Chev.) and rotary-cut beech (Fagus orientalis L.) Veneers. Build. Environ. 43, 469–474.

Dunky, M., Pizzi, A., 2002. Chapter 23 Wood adhesives.

Dunky, M., Pizzl, A., 2002. Wood adhesives. In: Adhesion Science and Engineering. Elsevier, pp. 1039–1103.

Edalat, H., Faezipour, M., Thole, V., Kamke, F.A., 2014. A new quantitative method for evaluation of adhesive penetration pattern in particulate wood-based composites: Elemental counting method. Wood Sci. Technol. 48, 703–712.

Endel, S., U, V., 2006. Puiduteadus. Tartu : Eesti Metsaselts.

European Commission, 2016. European Atlas of Forest Species. European Commission.

Ferdosian, F., Pan, Z., Gao, G., Zhao, B., 2017. Bio-based adhesives and evaluation for wood composites application. Polymers (Basel). 9.

Follrich, J., Teischinger, A., Gindl, W., Müller, U., 2007. Effect of grain angle on shear strength of glued end grain to flat grain joints of defect-free softwood timber. Wood Sci. Technol. 41, 501–509.

Follrich, J., Vay, O., Veigel, S., Müller, U., 2010. Bond strength of end-grain joints and its dependence on surface roughness and adhesive spread. J. Wood Sci. 56, 429–434.

Food and Agriculture Organization of the United Nations, 2020. Rome, 2020 61.

Forest Products Laboratory - USDA, 2010. Wood Handbook: Wood as an Engineering Material. USDA - Gen. Tech. Rep. General Te, 508.

Forest Products Laboratory (U.S.), 1962. The Manufacture of Veneer. Art, Arms Armour An Int. Anthol.

Forss, K.G., Fuhrmann, A., 1979. FINNISH PLYWOOD, PARTICLEBOARD, AND FIBERBOARD MADE WITH A LIGNIN-BASE ADHESIVE. For. Prod. J. 29, 39–43.

Frihart, C.R., 2004. Specific adhesion model for bonding hot-melt polyamides to vinyl.

Int. J. Adhes. Adhes. 24, 415–422.

Frihart, C.R., 2013. Wood Adhesion and Adhesives Chapter 9, In: Handbook of Wood Chemistry and Wood Composites, Second ed., Roger Rowell, Editor, by CRC Books, 2013, pp.255 -319.

Gardner, D.J., McGinnis, G.D., 1988. Comparison of the Reaction Rates of the Alkali-Catalyzed Addition of Formaldehyde to Phenol and Selected Lignins. J. Wood Chem. Technol. 8, 261–288.

Gavrilovic-Grmusa, I., Miljkovic, J., Djiporovic-Momcilovic, M., Radosevic, G., 2008. Penetration of urea-formaldehyde adhesives in wood tissue, part I: Radial penetration of UF adhesives into beech. Glas. Sumar. Fak. Fac. For. 39–48.

Gent, A.N., Lai, S.-M., 1995. Adhesion and Autohesion of Rubber Compounds: Effect of Surface Roughness. Rubber Chem. Technol. 68, 13–25.

Grand View Research, 2019. Global wood adhesives market size, share, industry report, 2019-2025.

Gray, V.R., 1962. The wettability of wood. For. Prod. J. 12, 452–461.

He, G., Riedl, B., 2004. Curing kinetics of phenol formaldehyde resin and wood-resin interactions in the presence of wood substrates. Wood Sci. Technol. 38, 69–81.

Hickey, M., King, C., 2001. The Cambridge Illustrated Glossary of Botanical Terms. Kew Bull.

Hill, C., 2006. Wood modification: chemical, thermal and other processes.

Hunt, C.G., Frihart, C.R., Dunky, M., Rohumaa, A., 2018. Understanding wood bonds-going beyond what meets the eye: A critical review. Rev. Adhes. Adhes. 6, 369–463.

Johnson, R.P.A., 1947. Mechanical properties of aspen. Aspen Rep., 16 p.

Johnson, S.E., Kamke, F.A., 1992. Quantitative Analysis of Gross Adhesive Penetration in Wood Using Fluorescence Microscopy. J. Adhes. 40, 47–61.

Kamke, F.A., Lee, J.N., 2007. Adhesive penetration in wood - A review. Wood Fiber Sci. 39, 205–220.

Keskkonnaagentuur, 2018. Aastaraamat Mets 2018.

Khoo, P.S., Chin, K.L., Hng, P.S., Bakar, E.S., Lee, C.L., Go, W.Z., Dahali, R., 2019. Physical properties and bonding quality of laminated veneer lumber produced with veneers peeled from small-diameter rubberwood logs. R. Soc. Open Sci. 6.

Kottes, A.B., Reinhardt, R., Frick, J., Bertoniere, N., 1986. Formaldehyde release from wood products. ACS Symposium. Amer Chem. Soc. 316, 52–66.

Kumar, R.N., Pizzi, A., 2019. Adhesives for wood and lignocellulosic materials, Adhesives for Wood and Lignocellulosic Materials.

Laborie, M.P.G., Salmén, L., Frazier, C.E., 2006. A morphological study of the wood/phenol-formaldehyde adhesive interphase. J. Adhes. Sci. Technol. 20, 729–

741.

Lee, W.-J., Chang, K.-C., Tseng, I.-M., 2012. Properties of phenol-formaldehyde resins prepared from phenol-liquefied lignin. J. Appl. Polym. Sci. 124, 4782–4788.

Li, G., Wu, Q., He, Y., Liu, Z., 2018. Surface roughness of thin wood veneers sliced from laminated green wood lumber. Maderas Cienc. y Tecnol. 20, 3–10.

Luostarinen, K., Verkasalo, E., 2000. Birch as sawn timber and in mechanical further processing in Finland. A literature study, Silva Fennica Monographs.

Lutz, J.F., 1974. Techniques for Peeling, Slicing, and Drying Veneer. US Prod Lab Res Pap.

LUTZ JF, 1971. Wood and Log Characteristics Affecting Veneer Production. U S For. Prod Lab, Res Pap FPL 150.

Mackes, K.H., Lynch, D.L., 2001. The effect of aspen wood characteristics and properties on utilization. Sustain. Aspen West. Landscapes Symp. Proc. 429-440\r460.

Maier, E., 2008. The Wood Database [WWW Document]. URL http://www.wood-database.com/ (accessed 5.1.21).

Marra, A.A., 1992. Technology of wood bonding : principles in practice. Van Nostrand Reinhold, New York.

Mays, G.C., Hutchinson, A.R., 2009. Adhesive classification and properties. In: Adhesives in Civil Engineering. Cambridge University Press, pp. 30–75.

Myers, G., 1985. Wood adhesives in 1985: status and needs. For. Prod. Res. Soc. 119–156.

Nees, J.L., Reeb, J., Funck, J.W., 2004. Relating traditional surface roughness measures to gluebond quality in plywood. For. Prod. J. 54, 67–73.

Neese, J., 1997. Characterizing veneer roughness and glue-bond performance in Douglas-fir plywood. oregon state Univ.

NORRIS, C.B., WERREN, F., McKINNON, P.F., 1961. The Effect of Veneer Thickness and The Grain Direction on The Shear Strength of Plywood.

Olivares, M., Guzmán, J.A., Natho, A., Saavedra, A., 1988. Kraft lignin utilization in adhesives. Wood Sci. Technol. 22, 157–165.

Ollinmaa, P., 1955. Koivun vetopuun anatomisesta rakenteesta ja ominaisuuksista. Acta For. Fenn. 64.

Packham, D.E., 2003. Surface energy, surface topography and adhesion. Int. J. Adhes. Adhes. 23, 437–448.

Paris, J.L., Kamke, F.A., 2015. Quantitative wood-adhesive penetration with X-ray computed tomography. Int. J. Adhes. Adhes. 61, 71–80.

Petković, G., Vukoje, M., Bota, J., Preprotić, S.P., 2019. Enhancement of polyvinyl acetate (PVAc) adhesion performance by SiO2 and TiO2 nanoparticles. Coatings

9, 1–17.

Pizzi, A., Mittal, K.L., 2011. Handbook of Adhesive Technology; Second Edition, Revised and Expanded, Marcel Dekker Inc. Elsevier Science B.V.

Plant For A Future, 2021. Alnus incana - (L.)Moench. [WWW Document]. https://pfaf.org/user/Plant.aspx?LatinName=Alnus+incana.

Polymer Science Learning Center, 2021. Poly(Vinyl Acetate).

Pot, G., Denaud, L.E., Collet, R., 2015. Numerical study of the influence of veneer lathe checks on the elastic mechanical properties of laminated veneer lumber (LVL) made of beech. Holzforschung 69, 337–345.

PuuProffa, 2021. GREY ALDER [WWW Document]. https://puuproffa.fi/puutieto-2-2/species/harmaaleppa-2/?lang=en.

Qin, L., Lin, L., Fu, F., 2016. Microstructural and micromechanical characterization of modified urea-formaldehyde resin penetration into wood. BioResources 11, 182–194.

Rath, W., Müller, B., 2005. Formulierung von Kleb- und Dichtstoffen. Coat. Int. 38, 15.

Rittiphet, C., Dumyang, K., Matan, N., 2021. Effect of pre-mechanical compression on free water removal, drying collapses and associated internal voids of oil palm wood. Eur. J. Wood Wood Prod. 1–16.

Rohumaa, A., Hunt, C.G., Hughes, M., Frihart, C.R., Logren, J., 2013. The influence of lathe check depth and orientation on the bond quality of phenol-formaldehyde - Bonded birch plywood. Holzforschung 67, 779–786.

Ryu, J., Imamura, Y., Takahashi, M., Kajita, H., 1993. Effect of molecular weight and some other properties of resins on the biological resistance of phenolic resin treated wood. Mokuzai Gakkaishi 39, 486–492.

Salmi, J., 1987. [Wood properties and uses of birch, Betula spp.]. [Finnish].

Schultz, J., Nardin, M., 2003. Theories and mechanisms of adhesion, Handbook of Adhesive Technology, A. Pizzi, and K. L. Mittal (2nd ed.), 53-67. New York: Marcel Dekker.

Sonnenschein, M.F., 2015. Polyurethanes science, technology, markets, and trends. John Wiley & Sons, Inc.

Stat.ee, 2019. Stat.ee, Αγαη.

Stehr, M., Johansson, I., 2000. Weak boundary layers on wood surfaces. J. Adhes. Sci. Technol. - J ADHES SCI TECHNOL 14, 1211–1224.

Stehr, M., Seltman, J., Johansson, I., 1999. Laser Ablation of Machined Wood Surfaces. 1. Effect on End-Grain Gluing of Pine (Pinus silvestris L.) and Spruce (Picea abies Karst.) 53, 93–103.

Stelte, W., Holm, J.K., Sanadi, A.R., Barsberg, S., Ahrenfeldt, J., Henriksen, U.B., 2011. A study of bonding and failure mechanisms in fuel pellets from different biomass resources. Biomass and Bioenergy 35, 910–918.

Stumbo, D., 1963. Surface texture measurement methods. For. Prod J 7, 299–304.

Tarmeko Group, 2020. Wood composites [WWW Document].

Tejado, A., Peña, C., Labidi, J., Echeverria, J.M., Mondragon, I., 2007. Physico-chemical characterization of lignins from different sources for use in phenol-formaldehyde resin synthesis. Bioresour. Technol. 98, 1655–1663.

Tout, R., 2000. Review of adhesives for furniture. Int. J. Adhes. Adhes. 20, 269–272.

Turunen, M., Alvila, L., Pakkanen, T.T., Rainio, J., 2003. Modification of phenol-formaldehyde resol resins by lignin, starch, and urea. J. Appl. Polym. Sci. 88, 582–588.

Ülker, O., 2016. Wood Adhesives and Bonding Theory. Adhes. - Appl. Prop.

United Nations Economic Commission for Europe, 2014. Estonia country market statement 72-nd sess, 18–21.

Vázquez, G., Rodríguez-Bona, C., Freire, S., González-Álvarez, J., Antorrena, G., 1999. Acetosolv pine lignin as copolymer in resins for manufacture of exterior grade plywoods. Bioresour. Technol. 70, 209–214.

Veigel, S., Müller, U., Keckes, J., Obersriebnig, M., Gindl-Altmutter, W., 2011. Cellulose nanofibrils as filler for adhesives: Effect on specific fracture energy of solid wood-adhesive bonds. Cellulose 18, 1227–1237.

Vick, C.B., 1999. Adhesive Bonding of Wood Materials. Wood Handb. - Wood as an Eng. Mater. 9-1-9–24.

Vineerimaalim, 2020. Vineeri ABC [WWW Document]. Vineerimaailm. URL https://www.vineerimaailm.ee/vineeri-abc (accessed 5.1.21).

Wang, W., Yan, N., 2005. Characterizing liquid resin penetration in wood using a mercury intrusion porosimeter. Wood Fiber Sci. 37, 505–513.

Wei, S., Shi, J., Gu, J., Wang, D., Zhang, Y., 2012. Dynamic wettability of wood surface modified by acidic dyestuff and fixing agent. Appl. Surf. Sci. 258, 1995–1999.

Zhou, X., Du, G., 2018. Applications of Tannin Resin Adhesives in the Wood Industry. Intech 32, 137–144.

APPENDICES

Appendix 1 Table of Log Peeling Information

Log information table									
Species (Log Number)	Unique Code	Soaking Temperature °C and time	MC% of green log	Veneer Thickness (mm)	Peeling Speed m/min	Drying temperature °C	Dryer MC (g/kg)	MC% of Dried Veneer	Drying Time (MIN)
BA1	1.0 BA 1.1.40.170	40°C and 24 Hours	77%	1	60	170	420 - 580	4.32%	2 min 15 Sec
BA2	1.0 BA 2.1.40.170	40°C and 24 Hours	79%	1	60	170	420 - 580	4.20%	2 min 20 sec
GA1	1.0 GA 1.1.40.170	40°C and 24 Hours	77%	1	60	170	420 - 580	3.93%	2 min
GA2	1.0 GA 2.1.40.170	40°C and 24 Hours	75.80%	1	60	170	420 - 580	3.87%	2 min
Bir1	1.0 Bi. 1.1.40.170	40°C and 24 Hours	75.60%	1	60	170	420 - 580	4.64%	2 min 20 sec
Bir2	1.0 Bi. 2.1.40.170	40°C and 24 Hours	74.30%	1	60	170	420 - 580	4.97%	2 min
AS1	1.0 As. 1.1.40.170	40°C and 24 Hours	71%	1	60	170	420 - 580	3.76%	1 min 50 sec
AS2	1.0 As. 2.1.40.170	40°C and 24 Hours	71.60%	1	60	170	420 - 580	3.76%	1 min 50 sec
BA1	1.5 BA 1.1.40.170	40°C and 24 Hours	70.60%	1.5	60	170	420 - 580	3-6%	2 min 30 sec
BA2	1.5 BA 2.1.40.170	40°C and 24 Hours	73.43%	1.5	60	170	421 - 580	3-6%	3 min 30 sec
GA1	1.5 GA 1.1.40.170	40°C and 24 Hours	71.29%	1.5	60	170	422 - 580	3-6%	4 min 30 sec

GA2	1.5 GA 2.1.40.170	40°C and 24 Hours	69.67%	1.5	60	170	423 - 580	3-6%	5 min 30 sec
Bir1	1.5 Bi. 1.1.40.170	40°C and 24 Hours	68.48%	1.5	60	170	424 - 580	3-6%	2 min 20 sec
Bir2	1.5 Bi. 2.1.40.170	40°C and 24 Hours	69.87%	1.5	60	170	425 - 580	3-6%	2 min 20 sec
AS1	1.5 As. 1.1.40.170	40°C and 24 Hours	70.35%	1.5	60	170	426 - 580	3-6%	2 min 25 sec
AS2	1.5 As. 2.1.40.170	40°C and 24 Hours	69.68%	1.5	60	170	427 - 580	3-6%	2 min 25 sec
AS1	2.6 AS 1.1.40.170	40°C and 24 Hours	70.45%	2.6	60	170	420 - 580	4.32%	5 min 50 sec
AS2	2.6 AS 2.1.40.170	40°C and 24 Hours	69.71%	2.6	60	170	420 - 580	4.32%	5 min 50 sec
BA1	3.0 BA 1.1.40.170	40°C and 24 Hours	74.50%	3	60	170	420 - 580	3.81%	7 min
BA2	3.0 BA 2.1.40.170	40°C and 24 Hours	76.90%	3	60	170	420 - 580	3.81%	7 min
GA1	3.0 GA 1.1.40.170	40°C and 24 Hours	71.87%	3	60	170	420 - 580	4.08%	6 min
GA2	3.0 GA 2.1.40.170	40°C and 24 Hours	72.23%	3	60	170	420 – 580	4.08%	6 min
Bir1	3.0 Bi 1.1.40.170	40°C and 24 Hours	73%	3	60	170	420 – 580	4.78%	5 min 10 sec
Bir2	3.0 Bi 2.1.40.170	40°C and 24 Hours	72.60%	3	60	170	420 – 580	4.78%	5 min 10 sec
AS1	3.0 AS 1.1.40.170	40°C and 24 Hours	72.60%	3	60	170	420 – 580	3.45%	6 min 20 sec
AS2	3.0 AS 2.1.40.170	40°C and 24 Hours	71.90%	3	60	170	420 – 580	3.45%	6 min 20 sec

Appendix 2 Table of Surface Roughness Profiles of Four Species

	Surface Roughness Profile Parameters	Black Alder			Birch			Gray Alder			Aspen			
	Veneer Thickness	1.0 (mm)	1.5 (mm)	3.0 (mm)	1.0 (mm)	1.5 (mm)	3.0 (mm)	1.0 (mm)	1.5 (mm)	3.0 (mm)	1.0 (mm)	1.5 (mm)	2.6 (mm)	3.0 (mm)
Ra (μm)	Samples from the bark side of the Log	11.0	12.5	15.1	9.5	13.7	13.6	15.2	14.8	16.9	20.8	21.3	15.7	21.2
	Samples from the Middle of the Log	9.8	13.2	12.7	11.1	12.6	13.3	14.3	16.3	17.5	18.1	22.1	19.5	24.1
	Samples from the pith side of the Log	10.8	13.8	11.5	11.5	13.0	12.3	17.8	15.5	14.8	21.6	20.4	14.9	22.4
	Mean	10.5	13.2	13.0	10.7	13.1	13.1	15.8	15.5	16.4	20.2	21.3	16.7	22.6
	SD	2.0	3.4	3.2	2.1	3.7	2.5	4.0	3.5	3.4	5.5	5.0	5.9	5.2
Rq (μm)	Samples from the bark side of the Log	14.3	16.0	19.4	13.0	17.9	18.1	19.0	18.7	21.3	26.1	27.1	20.1	26.6
	Samples from the Middle of the Log	12.9	16.8	16.4	14.9	16.7	17.6	18.0	20.5	22.0	22.8	27.8	24.7	30.3
	Samples from the pith side of the Log	14.0	17.6	14.9	15.5	17.1	16.3	22.1	19.6	18.7	27.1	25.8	19.0	28.0
	Mean	13.7	16.8	16.8	14.5	17.2	17.4	19.7	19.6	20.7	25.3	26.9	21.2	28.3
	SD	2.4	4.2	4.0	2.7	4.5	3.1	4.7	4.2	4.3	6.6	5.9	7.1	6.3
Rz (μm)	Samples from the Bark side of the Log	81.2	88.6	104.3	79.2	98.6	104.5	97.1	97.9	106.8	130.2	142.2	110.1	133.8
	Samples from the Middle of the Log	76.7	90.5	90.5	86.7	95.2	100.4	95.1	105.0	110.4	119.5	141.9	129.5	149.7

	Samples from the Pith side of the Log	80.2	93.9	85.3	91.5	96.1	95.6	110.6	102.5	96.4	138.0	134.8	102.7	110.5
	Mean	79.3	90.9	92.8	85.8	96.6	100.4	101.0	101.7	104.5	129.2	139.6	114.0	141.0
	SD	10.9	18.1	17.4	12.0	18.8	14.2	20.0	18.2	18.4	27.2	24.2	32.2	27.0

Appendix 3 Table of Mean Adhesive Bond Strength

Mean Adhesive Bond Strength				
Species	Veneer Thickness (mm)	Adhesives	Bond Strength (N/mm²)	Standard Deviation
Black Alder	1.0	PU	6.28	1.04
	1.0	PVAc	5.21	0.90
	1.0	PF	6.72	1.08
	1.0	LPF	5.18	0.74
	1.5	PU	5.41	0.82
	1.5	PVAc	5.33	1.14
	1.5	PF	7.45	1.24
	1.5	LPF	7.06	0.93
	3.0	PU	5.35	1.27
	3.0	PVAc	7.14	1.49
	3.0	PF	8.81	1.42
	3.0	LPF	8.46	1.69
Grey Alder	1.0	PU	4.78	0.69
	1.0	PVAc	5.52	0.87
	1.0	PF	6.62	0.83
	1.0	LPF	6.09	0.76
	1.5	PU	5.28	1.00
	1.5	PVAc	6.58	0.80
	1.5	PF	6.88	0.97
	1.5	LPF	7.84	1.10
	3.0	PU	6.46	1.29
	3.0	PVAc	7.49	2.08
	3.0	PF	8.45	1.34
	3.0	LPF	9.50	1.15
Birch	1.0	PU	5.93	1.06
	1.0	PVAc	5.26	0.72
	1.0	PF	6.92	0.97
	1.0	LPF	6.78	0.84
	1.5	PU	5.63	0.84
	1.5	PVAc	5.61	0.77
	1.5	PF	8.16	0.84
	1.5	LPF	7.42	1.24
	3.0	PU	5.38	0.97
	3.0	PVAc	8.42	2.39
	3.0	PF	11.70	1.58
	3.0	LPF	9.81	1.67
Aspen	1.0	PU	5.15	0.88
	1.0	PVAc	5.61	0.77

	1.0	PF	5.46	0.70
	1.0	LPF	5.33	0.73
	1.5	PU	6.02	1.01
	1.5	PVAc	5.94	0.95
	1.5	PF	6.87	1.02
	1.5	LPF	5.70	0.65
	2.6	PU	6.70	0.76
	2.6	PVAc	7.00	0.97
	2.6	PF	9.90	1.68
	2.6	LPF	6.82	1.12
	3.0	PU	6.54	1.37
	3.0	PVAc	6.63	1.24
	3.0	PF	10.29	1.70
	3.0	LPF	8.00	1.46