TALLINNA TEHNIKAÜLIKOOL
TALLINN UNIVERSITY OF TECHNOLOGY

Department of Materials and Environmental Technology

DEVELOPMENT OF HEMP HURDBOARD FROM FORMALDEHYDE-FREE RESINS

FORMALDEHÜÜDIVABADE VAIKUDE BAASIL KANEPILUUPLAATIDE VÄLJAARENDAMINE

MASTER THESIS

Student: Micah Onyedikachi Tobias

Student code: 174637KVEM

Supervisor: Heikko Kallakas, Early Stage Researcher

Tallinn, 2019

AUTHOR’S DECLARATION

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

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Author: ....
/signature /

Thesis is in accordance with terms and requirements

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Supervisor: …..........................
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Accepted for defence

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Chairman of theses defence commission: ....
/name and signature/

Department of Materials and Environmental Technology

THESIS TASK

Student: Micah Tobias, 174837KVEM

Study programme: KVEM 12/15 - Technology of Wood and Plastics

Main specialty: Wood Technology

Supervisor(s): Early Stage Researcher, Heikko Kallakas, +3726202910

Thesis topic:

(in English) Development of Hemp Hurdboard from formaldehyde-free resins

(in Estonian) Formaldehüüdivabade vaikude baasil kanepiluuplaatide väljaarendamine

Thesis main objectives:

1. Investigating Urea Formaldehyde (UF) synthetic resin, Acrodur resin and Soyad™ resin for the production of hemp hurdboard.
2. Manufacture of hemp hurdboard with different resin.
3. Investigating for the mechanical properties, water absorption, and thickness swelling, MOR, MOE, air permeability.
4. Analysis of the results of the Acrodur and Soyad™ resins and comparing the properties with synthetic resin (UF).

Thesis tasks and time schedule:

No	Task description	Deadline
1.	Evaluation of other journals and literatures	2nd Oct, 2017
2.	Project discussion and outlining process methodologies	27th Oct, 2017
3.	Assessment of availabile materials and sourcing of them	12th Nov, 2017
4	Preparation of materials and continuing sourcing of resins/adhesives	2nd Dec, 2017
5	Initial result preparation and appraisal for further plans	8th Dec, 2017
6	Laying groundwork for project I	14th Dec, 2017
7	Organisation of materials for further laboratory works	12th Jan, 2018
8	Reassessment of best standards in experimental works	2nd Mar, 2018
9	Manufacture of hemp hurdboard using Urea Formaldehyde	16th April, 2018

10	Project II report	6th June, 2018
11	Manufacture of hemp hurdboard using Acrodur resins	4th Sept, 2018
12	Project III report	15th Dec, 2016
13	Manufacture of hemp hurdboard using Soyad^{TM} resins	23rd Jan, 2019
14	Collation and evaluation of results.	20th May, 2019
15	Re-evaluating results and analysis with literature	20th May, 2019
16	Thesis pre-defence	24th May, 2019
17	Submission	30th May, 2019
18	Thesis defense	6th June, 2019

Language: English **Deadline for submission of thesis:** 30th May 2019

Student: Micah Onyedikachi Tobias ....“.......”...................2019

/signature/

Supervisor: Heikko Kalakas ……………………………….... “.......”.....................2019

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PREFACE

The author would like to thank everyone for their support and dedication toward the completion of this master's program most especially of the staff members of the Laboratory of Wood Technology, Tallinn University of Technology. My special thanks go to my supervisor, Heikko Kallakas for his guidance and unequivocal commitment towards making this thesis become a success.

The aim of this master thesis is to develop hemp hurdboard from formaldehyde-free resin. In this thesis, there is a comparison between the properties of hemp hurdboard and the traditional particleboard. With the obvious influence of formaldehyde emission on human's health, it is important that this research came forth in order to change the traditional method of manufacturing wood particleboard using urea formaldehyde and usher in alternative ways so as to attain environmental sustainability. Samples of the hemp hurdboard were produced and tested. Conclusively, the master's thesis was a success.

I also appreciate the support by Hempson OÜ in supplying the hemp hurd and also the interest they had shown in the research into hemp hurdboard. I acknowledge the support of BASF Europe for the donation of Acrodur® 3515 and Acrodur® 3558 resin used in this research and also Solenis North America for the donation of the soy-based adhesive such Soyad™ CA1025 and Soyad™ CA4740EU used in this research. The companies listed were very instrumental in this research.

Key words: Hemp, hurd, Soyad, Acrodur, Urea Formaldehyde, mechanical properties, physical properties, master thesis, particelboard, formaldehyde-free

LIST OF ABBREVIATIONS AND SYMBOLS

UF – Urea Formaldehyde

MOE – Modulus of Elasticity

MOR – Modulus of Rupture

MDI – Methylene Diphenyl diisocynate

TS – Thickness Swelling

WA – Water Absorption

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INTRODUCTION

Particleboard is nowadays one of the most acceptable wood-based composite materials for construction materials because of its low density, excellent thermal insulation, sound absorption, and wonderful machining properties. The primary lignocellulosic material used in the particleboard industry is wood (Shahzad A., 2011). However, there has been deliberate use of non-wood materials such as hemp, flax, and sorghum to replace the materials used for the production of particleboard while also investigating on the most suitable binder to be used (Ashori A., Dizaj M.Y., 2015).

Synthetic binders which are based on formaldehyde raw materials, such as, phenol formaldehyde, urea formaldehyde, and melamine-formaldehyde, and those based on isocyanate, such as Methylene diphenyl diisocyanate and pMDI, as the main binder to produce particleboards have been largely used in the wood materials industry (Silva et al., 2015). Bio-based resins are being researched on to produce environmentally friendly particleboard.

Particleboard is industrially manufactured from wood but research has shown that it can be made through different materials such as flax, hemp, coconut coir and sisal, sorghum fiber, etc. With this varying material exist different properties which can be exploited to solve varying problems such as in furniture making and construction (Ashori A., Dizaj M.Y., 2015). Since the use of other natural material aside wood is on the rise, this research is quite important to help with different natural materials such as hemp.

This thesis focuses on the use of hemp woods (*cannabis sativa*) in the manufacture of hemp particleboard (hemp hurdboard). Hemp was an obvious choice as it is an excellent natural fibre which has the ability to bind with polymers or adhesives. The hemp fibre predominately contains crystalline cellulose (56 – 70 wt. %), whereas hemicellulose and lignin are also contained at smaller proportions. The hurds is as important as the fibres as they can be used in making products such as discussed in this master's thesis.

The aim of this master thesis is to develop hemp hurdboard from formaldehyde-free resin. The formaldehyde-free resins are used in comparison with the traditional method of using wood bonded with urea formaldehyde resin in order to find alternative ways of manufacturing particleboard using sustainable materials. With this fact, the type of resin used for the hurdboard will be varied and measured in order to ascertain if the mechanical properties obtained from the bio-based resin and

Acrylic resin will be significantly different from the accepted resin (UF) which is used in the industry. To accomplish this, the tasks of the research are as follows;

a) Investigating urea formaldehyde (UF) synthetic resin for the production of hemp hurdboard.

b) Investigating different Acrodur resins for the production hemp hurdboard.

c) Investigating different Soyad resins for the production of hemp hurdboard

d) Manufacture of hemp hurdboard with different resin.

e) Investigating for the mechanical properties, water absorption, and thickness swelling, MOR, MOE, air permeability.

f) Analysis of the results and comparing the properties with wood particleboard bonded with synthetic resin.

1. LITERATURE REVIEW

1.1 Hemp

Hemp (Cannabis Sativa) is an annual plant with relatively short cropping cycle, which is an important economic factor (Bo M., 2004). It is one of the oldest non-food crops known to man, the oldest discovered hemp fabric is dated 8000 BC (Lilholt H., Lawther J. M., 2000). Its cultivation is environmentally friendly, does not need pesticides. Hemp can be grown in a wide range of weather and environmental conditions. Traditional products obtained from hemp fibers includes ropes, twines, fabric, and paper. Along with all the vegetable fibers, hemp is one of the strongest and stiffest fibers (Table 1).

However, despite all the advantages of hemp, cultivation is forbidden in many countries worldwide due to some content of psychoactive substance THC (Pickering K.L. et. al., 2007).

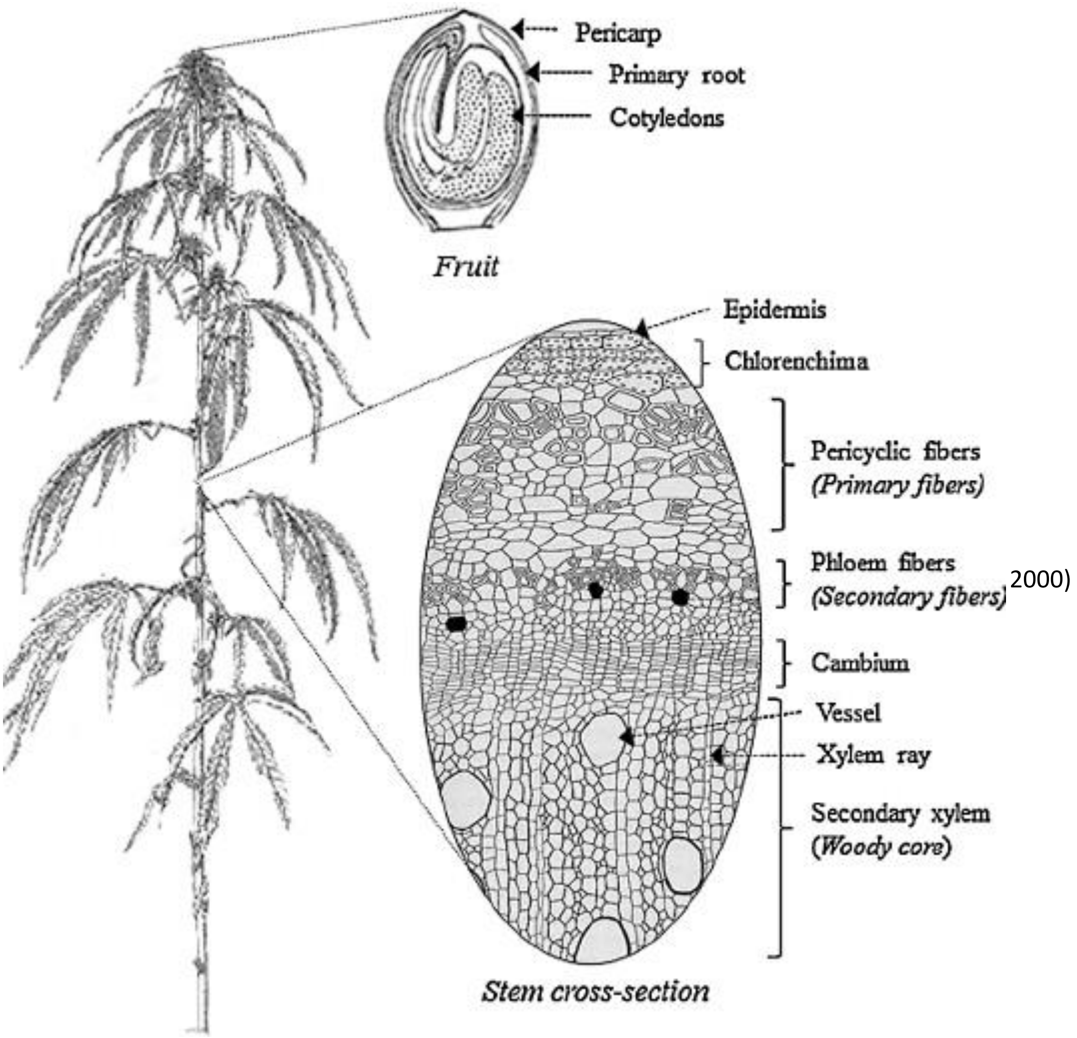

Figure 1.0 Hemp stem cross-section and Fruit Longitudinal (Lilholt H., Lawther J. M., 2000)

Table 1.0 Properties of different fibers (Lilholt, 2000)

Fiber		Diameter (μm)	Density (gcm^{-3})	Stiffness (GPa)	Strength (MPa)	Strain (%)	Thermal Expansion Coefficient (10^{-6} K^{-1})
Carbon	A B C	7 6 10	1.75 1.77 2.18	235 377 827	3530 4110 2200	1.5 1.2 0.27	-0.4 0.0 -1.45
Glass		10 – 20	2.54	72	3530	4.8	5.0
Aramid	A B	12 12	1.44 1.45	58 121	3600 3150	3.7 2.0	 -0.35
Polyethylene	A B	38 27	0.97 0.97	117 172	2650 3090	3.5 2.7	
Flax		19	1.4 - 1.5	50 – 70	500 – 900	1.5 – 4.0	
Hemp		**25**	**1.48**	**30 – 60**	**300 – 800**	**2.0 – 4.0**	
Jute		20	1.3 – 1.5	20 – 55	200 – 500	2.0 – 3.0	
Sisal			1.45	9 – 22	100 – 800	3.0 – 14.0	
Banana			1.4	7 – 20	500 – 800	1.0 – 4.0	
Pineapple			1.44	35 – 80	400 – 1600	0.8 – 1.6	
Cotton		20	1.5	6 – 10	300 – 600	6.0 – 8.0	
Softwood		33	1.4	10 – 50	100 – 170		
Hardwood		20	1.4	10 – 70	90 – 180		

Hemp fibers can be obtained from the plant by various methods. The most common is composed of two stages: retting and mechanical extraction. The first stage is retting and during this process, the hemp is placed in containers with hot water for a couple of days. The goal of this process is to degrade the tissue connecting single fibers. Mechanical extraction is made to separate fibers by mechanical way e.g. by rotating rollers (Pickering K.L. et. al., 2007).

Hemp fiber is a kind of natural fiber, which possesses high specific strength and modulus, low price, recyclability, easy availability. (Li, X et al., 2014) shows that a lot of researchers have been exploring particle board and fiberboard in recent years, which include the study of mechanical properties of the composites as well as finding an efficient way to improve the interfacial bonding properties between hemp fiber and polymeric matrices and fiber surface treatment on the mechanical performance of the composites (Khalfallah M., 2014). This research has led to increased knowledge of the utilization of hemp fibers and hurds for the production of composites materials, which can be utilized in the production of body parts in car manufacturing and also the production of particle boards and fiber boards.

1.2 Production of Particleboard

Particleboard consist of wood particles bonded with an adhesive under heat and pressure typically 145-180 °C and 0.5-3 MPa respectively depending on the adhesive, raw material, board density, and thickness. It usually contains 83 wt. % of wood residue and 11 wt. % adhesives. Unlike other thermoplastic composite, particleboard makes use of less amount of resin. (S.A. Sam-Brew, 2017).

Particleboards can be manufactured as either one-layered or three-layered (as shown in figure 1.1), which is produced with the core having over 60% of the particle while the face has 30%. The core has a larger particle size while the face contains finer particles.

Figure 1.1 Three – layered particleboard (Wang, D., Sun, X.S., 2002)

The manufacturing of particleboards involves quite a few steps which are abridged in the flow chart shown in Figure 1.2 and discussed in detail in following subsections.

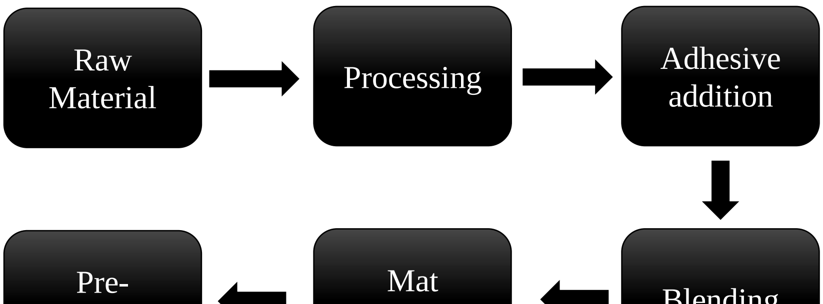

Figure 1.2 Particleboard manufacturing process (S.A. Sam-Brew, 2017)

1.2.1 Raw Materials needed for the Manufacture of Particleboard

Particleboard can be obtained from the residues of wood such as sawmill trims, chips, and sawdust. The prices vary as the shavings are the most expensive while sawdust is the cheapest. It is important to use residues from low-density wood species which are easier to process and are generally ideal because they are easily compacted. Low-density wood residue possesses an excellent adhesion characteristic which is useful in bonding wood particles together (Thygesen. A, 2006).

High level of the compact is needed so as to increase the mechanical properties of the particleboard. Most of the wood used in the manufacture of particleboard in Europe are softwoods obtained from trees such as spruce. While the greatest amount of the wood particles are dry in some cases it will need further drying so as to reduce the moisture content in the residues. A green drier is usually used to decrease the moisture content (MC) to about 6 - 8% before production starts. When wood residues contain a high moisture content, the mechanical properties of the particleboard decrease.

Figure 1.3 Kiln Drying (Sam-Brew S., 2017)

1.2.2 Adhesives used in the Manufacture of Particleboard

The most common and cheap glue used for the manufacture of particleboard manufacture is urea formaldehyde (UF) and phenol formaldehyde (PF). These water-based resins contain about 50% – 60% solid content and they are mostly thermosetting resins. UF is a good resin with a fast curing time (implying that they have shorter press time) and more importantly colourless, which means they particleboard won't have any coloration(Kozlowski, R., Helwig, M., 1998).

However, it is of note that UF resin has some disadvantages such as their low water resistance hence any product which uses UF wouldn't be suitable for an interior application as there will be the continuous release of formaldehyde emissions which is caused by hydrolysis of the weakly bonded formaldehyde. When melamine is fortified with UF resin due to its low solubility in water but this makes the resin more expensive compared with UF resin. Phenol formaldehyde (PF) resins can also be used in the manufacture of particleboards. PF resin is suitable for the exterior product because they have stronger bonds that are water-resistant, thus low formaldehyde release after board production. The shortcomings of PF resins is that it leaves a dark colour glue line on the particleboard and the fact that it requires a higher temperature and longer time to cure (Kozlowski, R., Helwig, M., 1998). The solid content of the adhesives determines the quantity of resin to be used. While a percentage of the total resin in relation to the dry weight of the wood residue is usually used when calculating the quantity of resin needed for the particleboard. For example, 11% of UF resin is normally used industrially when manufacturing particleboards (Sgriccia N., Hawley M.C., Misra M., 2008).

The quantity of resin used depends on the particle size of the wood particle. Usually, finer particles tend to consume to more resin solids because of their greater surface area while larger particle consumes less. Generally, the measure of adhesives used depends on the type of material used for the particleboard, the solid content of the resin and its particle size. In other to intensify the reaction rate, hardeners are added to the resin while wax may be added to increase the water resistant of the boards. Fire resistance materials may also be mixed with the adhesive so as to delay combustion in the particleboard. Depending on the type of resin used and the production method, the resin may be sprayed on the mat using a nozzle. Industrially, the mixture of the additives, water, and resin are blended in using a computerized system, which will eventually spray the mixture on the mat continuously.

Table 1.1. Physical and Chemical properties of resin (Khalfallah M. et. al., 2014)

Resin type	**PMDI**	**Acrylic**	**UF**
Brand Name	Lupranate M20	Acrodur 950L, 3515, 3558	Casco-Resin
Color/physical state	Dark amber liquid	Yellowish liquid	White-hazy liquid
Solid Content(%)	100	50	65
NCO content(%)	31.5	N/A	N/A
pH value	N/A	3 – 4	7.2 – 8.4
Density(g/cm^3)	1.22	1.2	1.27 – 1.30
Viscosity (mPa.s@20oC)	200	900-2500	100-340

1.2.3 Bioresin used for the Manufacture of Particleboard

Bio-resins is a natural and green adhesive which is a substitute for traditional synthetic resin such as UF and PF which can cause VOC's to the atmosphere thereby endangering human lives. A lot of research has been embarked on which develops with the sole aim of developing a high-performance green adhesive which is derived from different natural material such as oilseed rape and soybean which could be a replacement to the formaldehyde based resin with applications in building and furniture materials.

Bioresin is expected to be chemically stable, creating no toxic emission and renewable and sustainable. It is cheap and the raw materials should be easily available and biodegradable and importantly, water resistant. Decades ago, Soy-protein-based wood adhesives have been used as alternatives to petroleum-based adhesives with grander performance and economics. According to (Hamarneh, A. I. M., 2010), current research is focused on developing and commercializing four soy products:

1) A soy/phenol-resorcinol-formaldehyde (PRF) system for finger-jointing green lumber,
2) An upgraded waterproof product to substitute PF,
3) A foaming glue for plywood.
4) A developed water-resistant product to replace UF and
5) An epoxidized soybean oil (EBSO) is a good cross-link and is suitable for the production of thermosetting adhesives.

The term 'bio-derived adhesive' or bio-based adhesive can be defined as a natural eco-friendly adhesive which can be used in the production of furniture and construction materials. During the years, industrial applications of adhesive have been petroleum based and formaldehyde-based which invariably has implication for the environment. A number of the study had been made on the type of natural material that is suitable for the production of adhesives and they include soy-bean flour, tannins, lignins, carbohydrates, unsaturated oils, liquefied wood and wood welding by self-adhesion.

1.2.3.1 Types of Bio-based Adhesive

Tannin-Based Adhesive is a green adhesive that is gotten from the bark of a tree such as oak, mimosa, and chestnut. Tannin adhesives are used to replace synthetic resin such as UF and PF. In the past, several research had shown that hardeners mixed with tannin for the production of particleboard contain a low grade of formaldehyde which is still not sustainable (Jeong-Hun L., Junhyun K., Sumin K., Jeong T. K., 2012).

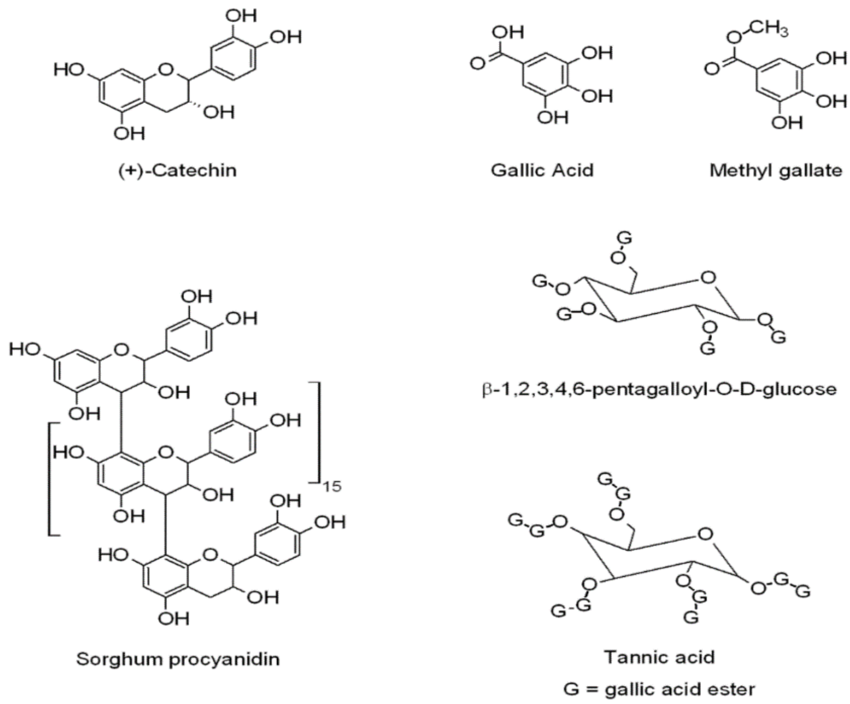

Figure 1.4 Compounds of tannin (Jeong-Hun L., Jisoo J., Sumin K. 2011)

There are two chemical compounds of tannin in nature and they are hydrolyzable tannin and condensed tannins. Hydrolyzable tannins include blends of simple phenols, such as pyrogallol and ellagic acid, and of esters of sugar, mostly glucose, with digallic acids (Pizzi) and gallic. During a study, condensed tannin was mixed with hexamine solution and a formaldehyde solution was used as a harderner. The tensile strength and flexural strength of the particleboard produced was similar to that of UF (Lee J.H et al, 2014).

Lignin is a glue mainly found in wood. It is present as part of the component in the structure of wood as it holds another component together such as cellulose and hemicellulose. During the pulping process or the Kraft process, the lignin content available as a by-product is in excess of 8 – 45%. During pulping, the lignin produced is the non-sulphonated lignin (Hamarneh, A. I. M., 2010).

Over the years, extensive research into lignin-based wood adhesives has not been fruitful when compared to its counterpart. Extensive research into chemically-modified lignins focused basically on methylation and epoxidation but this didn't yield reasonable result as the curing of conventional PF resin has taken over in industrial application thereby making it difficult for industries to look into changing adhesives. The barrier to continuous study of lignin has been the inconsistency of reproducibility of the study, which focused on the use of lignin. This presents a barrier to commercial development if different blends and source of lignin are going to give different properties (Roy A. K.; Sardar D.; Sen S. K., 1987).

(Roy A. K.; Sardar D.; Sen S. K., 1987) focused on using Lignin PF blend (lignin waste) as adhesives in making particleboard. Why the process is of intense interest is that it can bring physical strength and dimensional stability to the particleboard. Using this Lignin-PF resin for bonding particleboard shows great potential for the researcher investigating the use of lignin-based resin for making board panels. The research was concluded that the feasible replacement for PF is lignin mixed with 30% phenol which will be used for the production of particleboard.

Over the period of 2000 – 2005, a collective study on lignin extracted from wood using High-Pressure Hydrolysis (HPH) by Japanese and German researchers. The HPH-lignin is mixed with natural fiber (hemp, flax) was obtained through in a granule form when the mixture was passed through a small injection moulding machine. During this research, the mechanical properties of the test sample were compared to those of wood-thermoplastic composite and they were found to have comparable properties. The conditions of removal of lignin were gotten at 5 MPa at 250 ^{o}C and the separation of lignin is from steam at 0.3 MPa at 120 ^{o}C. During the extraction of lignin, 160kg of lignin was extracted from 1 tonne of wood.

Conclusively, the wood-like thermoplastic gotten through the HPH-process has excellent mechanical properties thereby making the HPH-process is feasible. The resins formed were used as thermosetting and cold setting exterior grade wood adhesives for Sapele veneer panels. The result shows that the resin is at par with the resin gotten from cashew nut (Lubi C. M. & Thachil E.T., 2007).

Cashew Nut Shell Liquid (CNSL) is an agricultural by-product of the Cashew Nut processing industry and it is a sustainable resource that has a long chain and m-substituted phenol which have shown potentials to be an excellent monomer for polymer production. The dark brown colour, viscous fluid has shown a lot of potentials in the production of adhesives (Jeong-Hun L., Sumin K. 2015). (Dinesh B., Anagha S. S., 2013) investigated its extraction, chemistry, and composition of CNSL so as to replace any petroleum based materials used for adhesive to a bio-based material due to its availability, sustainability and low cost. Since cashew nut is predominantly found in tropical and subtropics areas, there was quite a huge concern of its availability worldwide. Cashew is also a seasonal crop and there might be difficulty in harvesting the crop year round, which might also hinder productivity (Dinesh B., Anagha S. S., 2013).

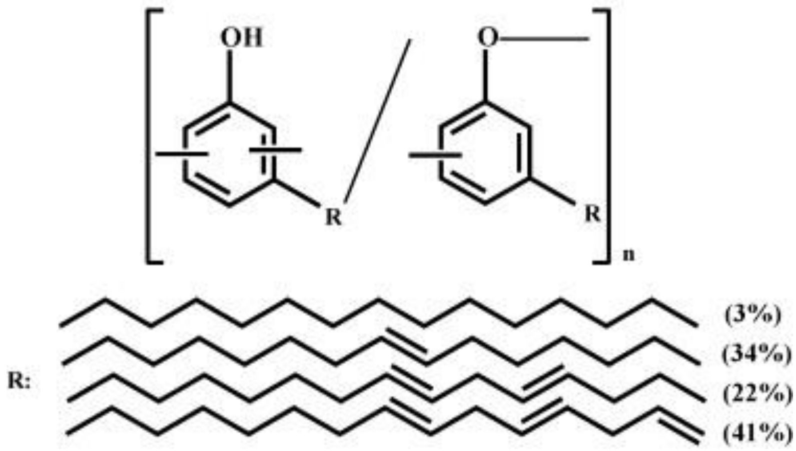

Figure 1.5 Components of CNSL(Jeong-Hun L., Sumin K. 2015)

CNSL contains four major components: 3-pentadecenyl phenol (cardanol), 5-pentadecenyl resorcinol (cardol), 6-pentadecenyl salicylic acid (anacardic acid) and 2-methyl, 5-pentadecenyl resorcinol (2-methyl cardol). CNSL is of immense interest as there are a lot of ways of application of the oil. CNSL can be applied in polymer and coating, production of additives, production of paint and primers, and also for resin synthesis and making adhesive (Dinesh B., Anagha S. S., 2013). (Lubi C. M. & Thachil E.T., 2007) was able use of CNSL in the production of particleboard, the heated mixture of CNSL, Phenol, and Hexamethylenetetramine was used as a resin. The particleboard produced was found to have excellent mechanical properties.

Carbohydrates: Over the centuries, polysaccharides (starch, hemicellulose, cellulose) have been used for adhesives. Due to its availability and low cost, starch-based adhesives are important. It is the second most important natural occurring polymer after cellulose which can be obtained mainly stalks, root and seed of staple crops such as rice and maize. UF resin has always been synthetic resin due to its easy availability and also its ability to be colourless in elevated temperature. In order to main excellent bondability oxidized starch blended with UF resin has excellent insulating properties, oil resistance and it is environmentally friendly (Ravindra V.et al., 2017).

When ionized starch reacts with UF, it decreases the drying time of starch and also improves the water resistance. Ultimately, the mixture will be excellent for particleboard production and also there will be a reduction in VOC emission.

However, in order to avoid formaldehyde emission, modified starch could be cross-linked with latex. Extensive research has gone into blending natural rubber and starch into making medium density fiber (MDF) board panels. The study showed that there were increased mechanical and physical properties when using this adhesive. The result indicates the feasibility of using this adhesive in a commercial quantity in the future (Li, J. et al., 2010). The disadvantage of this adhesive is the colour of the latex which could change the colour of the board panels.

Soya-based Adhesives: This is an adhesive based on using resin and soy-flour as an activator. The resin reacts to the protein content in the soy flour. Soy Flour has been extensively used in the time past because of its availability, low cost, and its environmental sustainability. Nevertheless, its hydrophilic nature has restricted the application of soy-flour based adhesives. A lot of research has been done to improve the hydrophilic nature of soy flour-based adhesives, including protein denaturing agent modification and cross linker modification (G. A. Amiral-Labat et al., 2017). In order to improve the water resistance, some synthetic resins such as phenol formaldehyde (PF) and melamine-urea-formaldehyde (MUF), can improve the water resistance of the adhesive. While these resins can really solve the problem of water resistance, there seems to be a problem; for example, MUF resins result in Volatile Organic Compounds (VOC) emissions, which can really affect the atmosphere. Moreover, PF resin commendably improves both the strength of bond and water resistance of the adhesive, but owing to its high pH value, it causes destruction to the soy protein and leads to a decrease in surface bond strength. The weight ratio of soy protein to PF could even be 1: 1 which will make the soy flour become more like a filler rather than soy flour-based adhesive. Another disadvantage of PF is that the curing temperature is also high (≥150 ◦C), and that might lead to the soy protein being burnt or "overcooked "which might is linking cationic resin. The dry soy flour initiates the reaction and consequently make effective bonding. The effect decreases the strength of the composite. Chemical industries are bringing up different Soy-based adhesives and one of those companies is Solenis Incorporated. Soyad™ is a soy-based adhesive produced by

Solenis Incorporated, which is consist of two component, which is, dry soy flour and a cross-linking cationic resin.

1.2.4 Pre-pressing

The mat is formed with a mould before they are pre-pressed. Pre-pressing is designed so as to reduce the thickness of the mat by compression (S.A. Sam-Brew (2017). Pre-pressing reduced mat size by removing the air before the formed mat is transferred into the hot press. After the mat is pre-pressed, the mould is removed before transferring the formed mat into the hot press. Pre-pressing the mat reduces the chances for the materials to spill out of the edges of the mat (Figure 1.6). The pre-pressing may be cold or hot and it is important to note that the pre-pressing helps to get heat energy into the mat. Pre-pressing to up to 3.86 MPa have been reported to improving the pressing condition and the board's mechanical properties. Industrially, there are two types of pre-presing namely, platen prepress and continuous prepress. A platen prepress operation allows for the process to be stopped while the mat is being prepressed while continuous preprepress allows for a continuous pressing in the machine line.

Figure 1.6 Pre-pressing of Particleboard

1.2.5 Hot Pressing

Hot pressing involves the transfer of heat and flow of gases. The material is densified due to the compacting influence of the two plates (upper and lower) and also through heat. Particleboards can be pressed in a batch press or continuous press. The continuous presses produce one long particleboard and the process continually keeps producing while the mat is formed whereas the batch presses are used in phases to manufacturing single particleboard. Most of these batch presses can make particleboards anywhere from 1.22 – 1.84 meters wide and 7.2 foot long (Sam-Brew S. A, 2017).

Figure 1.7 Hot pressing of Particleboard

The sequence used for hot-pressing comprises of blends of different factors such as type of resin used, the curing temperature of the adhesive, the pressure required, moistness of the pre-pressed mat, desired thickness, the projected density of the board to be manufactured and additives added. The temperature that the particleboard is pressed is determined by the type of adhesive used, behaviour of the adhesive when subjected to heat. For example, the PF adhesive normally cured at a between 175 °C to 180°C.

The pressing time of the particle also depends on the type of resin and how fast the resin cure and this is determined by the manufacturer. During hot pressing, the press is closed fast to avoid pre-cure of the bottom face in contact with the platen and ensure quick contact with the top platen. Once contact is made with the mat, the press is adjusted to close slowly to generate steam in the face layers in contact with the heated platen and force the steam into the core to heat and cure the resin.

2. MATERIALS AND METHODS

This chapter describes the materials used for the particleboard and also the resins used for this research. The chapter also extensively explain the process of the manufacture of the hemp hurdboard and also the why the adhesive used might have implication to the physical and chemical properties of the materials. The methods used for this research is consistent with what done in the industry. The research miniaturizes the manufacture of particleboard in the industry in a small laboratory scale.

2.1 Materials

2.1.1 Hemp Hurds

The hemp hurd was brought to the university by Hempson OU. The company has shown immeasurable effort in making sure that the research was progressive by supplying hemp hurd adequately. However, the hemp hurds was not sufficiently clean as there is some trace of fibers among the hurds which could affect the mechanical properties of the hurdboards. The fibers were handpicked so as to isolate the hurds. The hurds was not chemically treated.

Figure 1.8 Hemp hurd residue

2.1.2 Resins

Getting an effective resin for the research was quite a challenge as there were cost issues and local availability. Since the most industrial application of resins was only focused on the use of UF resins, it was quite difficult getting bio-based resins and formaldehyde-free resin. About 3 types of resins were used during this research for the manufacture of particleboards.

- Synthetic resin – urea formaldehyde
- Formaldehyde-free resin – Acrodur 3510 and Acrodur 3558
- Bio-based resin – Soyad™ CA4740 and Soyad™ CA1025

Synthetic Resin. The urea formaldehyde was supplied to us by Hexicon Incorporated. From the literature review, it is established that UF is predominately used for the production/manufacture of particleboard. Industrially, urea formaldehyde is preferred to other resins due to availability in the market, low cost, and resistance to water. During the research, different samples of wood particleboard and hemp hurdboard was produced using UF. The chemical and physical properties of the UF is as follows;

Table 1.2: Physical properties of the UF resin (Hexicon Manual)

Resin type	**UF**
Product Name	Casco-Resin
Colour	White-hazy liquid
Solid Content (%)	61
NCO content	N/A
pH value	7,2 – 8,4
Density (g/cm^3)	1,27 – 1,30
Viscosity (mPa.s @23°C)	100-340

Formaldehyde-free Resins. Due to the enactment of the ATCM regulation, a lot of research has gone into the formulation and production of resin containing little or no formaldehyde so In order to use formaldehyde-free resin so as reduce the implication of formaldehyde emission on our health (Khalfallah M. et al. 2014). The research found out that companies like BASF have succeeded in producing resins that are formaldehyde free such as Acrodur. Acrodur is acrylic and water-based resin, which is formaldehyde free which is perfectly fit for natural fibers such as hemp, flax, kenaf, etc. During the research, two resins produced by BASF which is Acrodur 3515 and 3558. The chemical and physical properties of the resins are as follows;

Table 1.3: Physical properties of the Acrodur resin (Acrodur product manual)

Resin type	**Acrylic**	**Acrylic**
Product Name	Acrodur 3515	Acrodur 3558
Colour	Yellowish liquid	Yellowish liquid
Solid Content (%)	50	50
pH value	3 – 4	3 – 4
Density (g/cm^3)	1,2	1,2
Viscosity (mPa.s @23°C)	150 - 300	300-1500
Comment	Hard thermoset	Tough-Elastic thermoset

Bio-based Resin. Bio-based resin is adhesives that use environmentally friendly materials that exist in nature. In the development of bio-based resin, natural oil (soybean oil), carbohydrate and naturally occurring phenolic compound (tannin and lignin) are extracted and used in the production of the resins. In this research, a soy-based adhesive produced by Solenis Inc. will be used. Soyad™ adhesives is a water-based resin which contains about 70 – 90 % bio-based content which is prepared with soy flour and a cross-linking cationic resin. Although soyad is normally sprayed on the particles or the fibers, the soy flour will be mixed with water and the resin making it a slurry which will eventually be mixed in proportion in the mixer. During the research, two different types of hemp hurdboard will be manufactured using two different resin namely Soyad™ CA1025 and Soyad™ CA4740EU while Soyad™ TS8200 is the soy flour. The physical and chemical properties of the resins are as follows;

Table 1.4 Physical properties of the Soyad™ resin (Soyad™ product manual)

Resin type	**Cationic**	**Cationic**
Product Name	Soyad™ CA1025	Soyad™ CA4740EU
Colorur	Golden coloured liquid	Golden coloured liquid
Solid Content (%)	25	48
pH value	2.8	3.5
Density (g/cm^3)	1.07	1.13
Viscosity (mPa.s @23^{o}C)	175	175
Shell Life	60 days at 25^{o}C	60 days at 25^{o}C

2.2 Processing Methods

2.2.1 Manufacturing of the Hemp hurdboard using Urea Formaldehyde

Experimentally, the focus of this research is the production of 1 – layered hemp hurdboard or particleboard. The moisture content of the hemp hurdboard is determined by air-drying oven method which can be calculated by this equation.

Calculation of the moisture content on a wet-weight basis was done with the following equation 1:

Moisture content (%) = $\frac{W2-W3}{W2-W1}$ x 100% (1)

Where,

W1 = weight of container with lid;

W2 = weight of container with lid and sample before drying; and

W3 = weight of container with lid and sample after drying.

The moisture content is needed for determining the amount of resin that will be used. In order to achieve the desired standard of 600 - 700 kg/m^3, 1200g of hemp hurd residue was used for this research.

The amount of resin used, depends on many factors such as the solid content of the resin, the wt% of hardener and the type of resin used. For instance, UF resin required adding 11wt% of resin and a fifth of hardeners while Acrodur resin required 11% resin and no hardener is required.

Table 1.5: Adhesive information for the manufacturing of hemp hurdboard

Resin Type	**UF**	**Soyad CA1025**	**Soyad 4740EU**	**Acrodur 3515**	**Acrodur 3558**
Amount of Adhesive (wt% from hemp mass)	11	11	11	11	11
Amount of resin (wt% from solid content)	61	23	48	50	50
Amount of Hardener(g)	40,25	58,89	51,69	NIL	NIL
Amount of Water	NIL	56,80	NIL	NIL	NIL

The manufactured process of the hemp hurdboard commences with calculating the amount of resin too. The resin is thereafter mixed with the residue hemp hurd in the mixer. After mixing is completed, it is now transferred to a wooden frame of 400cm x 400cm in order to form the mat which is eventually pre-pressed inorder to compress the mat and remove air from it. The pre-pressed hemp mat was transferred to the hot-pressed so as to allow the resin to cure at elevated temperature of 180^{o}C. The pressing cycle is based on the thickness of the board and it involves 20 second of hot press closing time, 7 minutes holding time at 1.5 MPa and 180 °C, and 3 minutes degassing time to remove bubbles before transmitting to the pressure control to open the press for 1 minute.

The manufacturing technique of hemp hurdboard using Acrodur® resins and Soyad resins are quite similar to that of that UF. From the product description, we can determine the solid content of the resins and with this, we can find out how we calculate the amount of resin used and also with reference to Soyad resin, the Soy flour and also the amount of water needed.

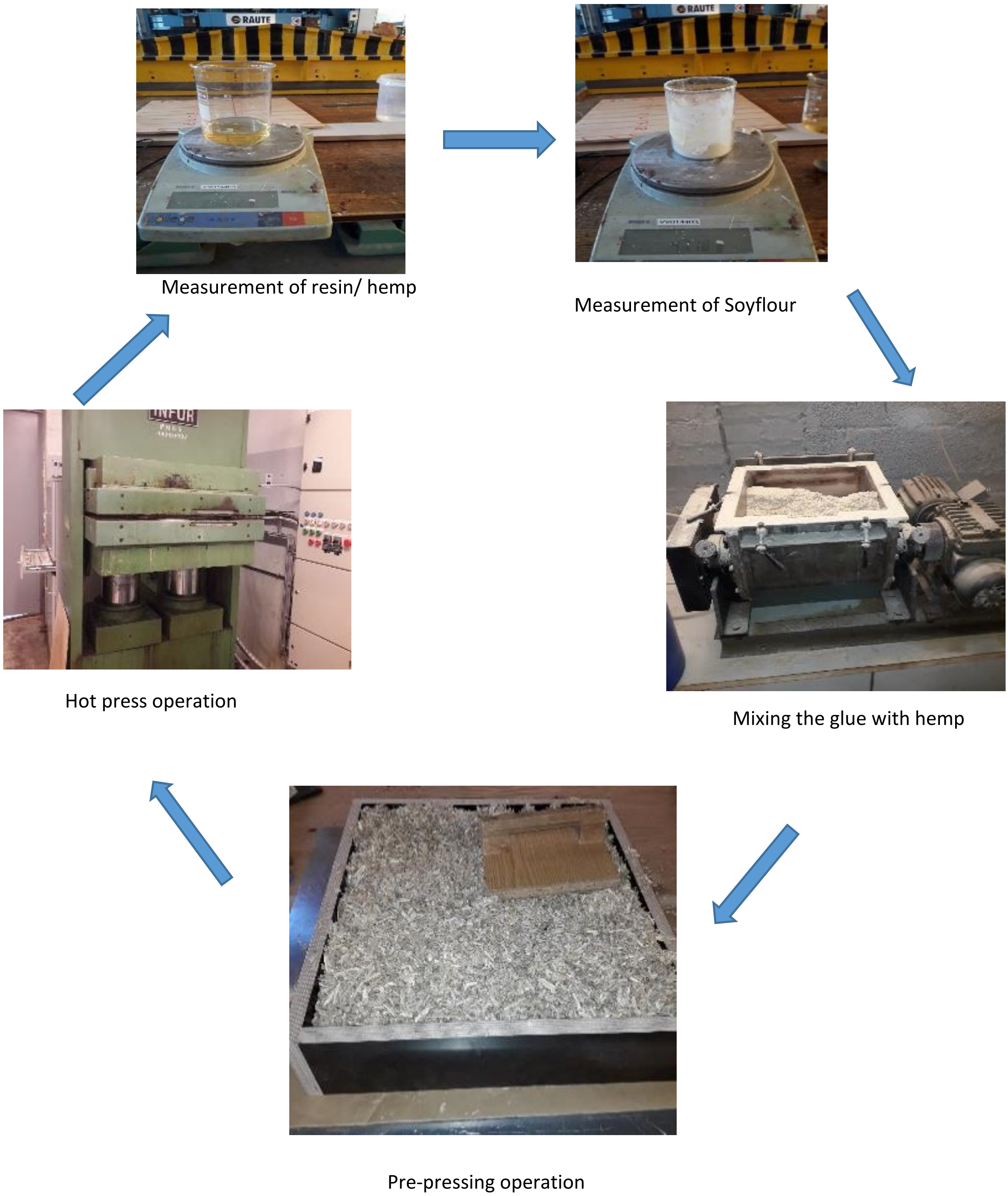

Figure 1.9 Schematic process of the manufacture of hemp hurdboard with Soyad resin

2.3 Analysis Methods

A total of 25 hemp hurdboard was produced, which is 5 board per resins. As outlined by the table 1.6, they samples consist of various standards with varying sizes. The material are cut into their various sizes as specified below. The evaluated test is as detailed in table 6 below. Strength properties of these boards was evaluated and then compared. Specimens are designated as shown in table 6.

Table 1.6: Testing Plan of samples

Test	Standard Number	Size	No of samples
Bending Strength	EVS-EN 310:2002	50 x 250 mm	10
Axial Withdrawal of Screw	EVS-EN 320:2011	65 x 50 mm	10
Tensile Strength	EVS-EN 319:2000	50 x 50 mm	10
Thickness Swelling	EVS-EN 317:2000	50 x 50 mm	5
Air Permeability	EVS-EN 12114:2000	100 x 100 mm	5
Microscopic Investigation		A small sample was cut	

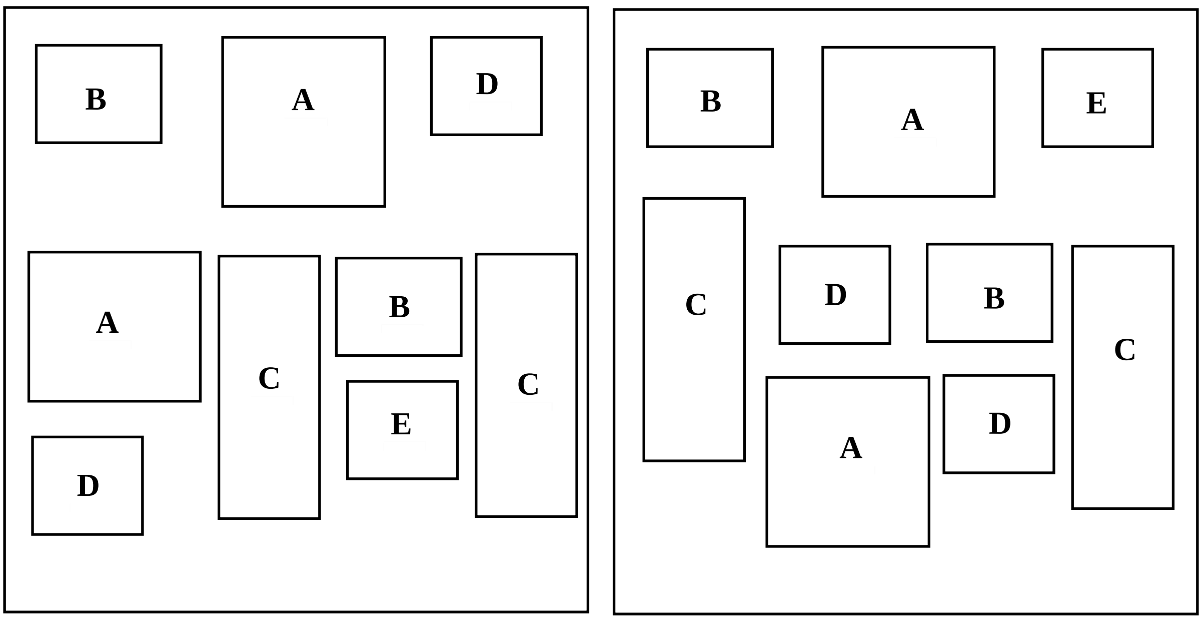

Figure 2.0. Cutting out plan of the samples A – Air Permeability, B – Axial Withdrawal of Screw
C – Bending Strength, D – Tensile Strength, E – Thickness Swelling

2.3.1 Determination of Tensile Strength

The test is carried out in harmony with the international standard EN 319:2000. For each of the material type, 10 samples were tested and a total of 50 specimens for was taken from all the materials. The test sample is measured at 50 mm x 50 mm as presented in Figure 2.1, while the thickness of each sample was taken and recorded before testing. A rectangular plywood measuring 65 mm × 50 mm is glued to the test piece using PVA glue so as to enable the test piece to be mounted on the test rig. The samples with PVA glue on plywood were put under weight and left to cure for at for 1 day. The test was conducted using the electromechanical universal testing system Instron 5688. In performing the test, the samples were positioned between two clasps point of the metal jig and the sample was loaded until it failed.

Figure 2.1: Tensile Strength test sample

The tensile stress (*σ)* and strain (*ε)* of the specimens were determined as shown in equation 2:

$$\sigma = \frac{F}{A}, \quad \varepsilon = \frac{\mathrm{dlo}}{\mathrm{lo}} \qquad (2)$$

Where

σ – tensile stress value, MPa;

F – force N;

A – cross-sectional area of the sample, mm^2;

ε – strain value

lo – is the gauge length of the test piece in mm, dlo – is the increase in the specimen length between the gauge marks, mm;

Moreover, the nominal strain (εt) and Young's modulus of elasticity (Et) was calculated as depicted in equation 3 and 4, respectively:

$$\varepsilon t = \frac{\Delta L}{L}, \tag{3}$$

$$Et = \frac{\sigma 2 - \sigma 1}{\varepsilon 2 - \varepsilon 1}, \tag{4}$$

Where,

εt – nominal tensile strain, expressed as a dimensionless ratio or percentage, %;

L– the initial distance between grips, mm;

ΔL – an increase of the distance between grips, mm;

Et – Young's modulus of elasticity, MPa;

σ1 – initial stress;

σ2 – final stress;

ε1 – initial strain;

ε2 – final strain;

Δσ – Difference in applied tensile stress between the two strain points, MPa;

Δε – Difference between the two strain points

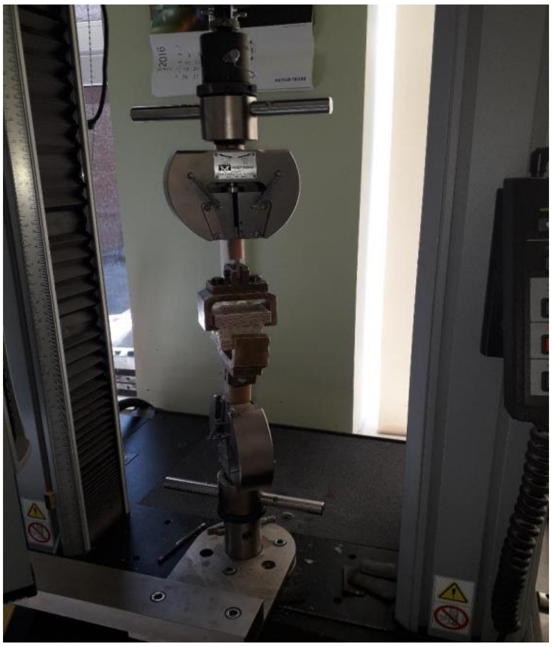

Figure 2.2 Tensile strength perpendicular to the plane of the board

2.3.2 Determination of Flexural Strength

The flexural test was used to determine the flexural strength and modulus of elasticity according to standard EVS EN 310:2002. 10 samples were taken from each material thereby making a total of 50 test specimen for all the particleboard. The dimension of the samples is 250mm x 50mm as shown in figure 2.3. Before commencing the test, the thickness of each sample was measured. The test was carried out using the electromechanical universal testing system Instron 5688 machine at a standard laboratory.

The following equation 5 shows the calculation for the flexural stress parameters:

$$\sigma f = \frac{3\mathrm{FL}}{2\mathrm{bh}^2}, \tag{5}$$

Where

σf – MOR;

F – Applied force N;

L – Span (mm);

b – Width (mm) of the specimen;

h – Thickness (mm) of the specimen

Equation 6 below was used to calculate the flexural strain parameters:

$$\varepsilon f = \frac{600\mathrm{sh}}{l^2}\,\%, \tag{6}$$

Where

εf – Flexural strain in %

s – Deflection (mm);

h – Thickness (mm) of the test specimen;

L – Span (mm)

Figure 2.3: Flexural Strength test sample

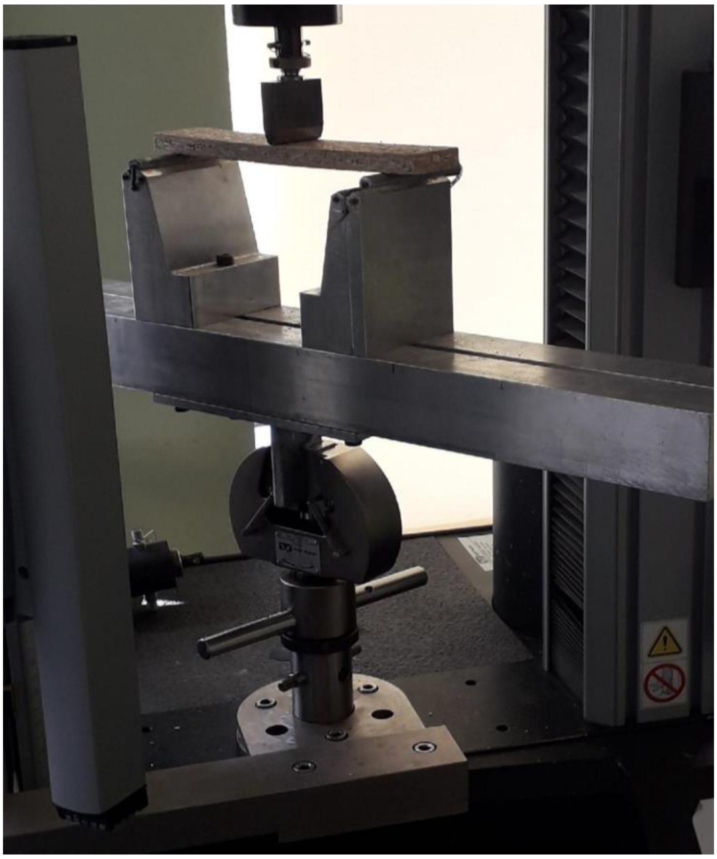

Figure 2.4: 3-point flexural strength test

2.3.2 Determination of Thickness Swelling and Water Absorption

This test is carried out in harmony with the international standard EVS-EN 317:2000 which is used to determine the dimensional change of particleboards when exposed to moisture. Test samples is a square which is measured as (50 ± 1) mm as shown in figure 2.9. Thickness swelling is determined by measuring the thickness after wholly dipping the test piece in water. The water bath is thermostatically controlled at a temperature of (20 ± 2) ^{o}C. The test piece itself is controlled to a constant mean relative humidity of (65 ± 5) % and a temperature of (20 ± 2) °C. The samples are placed so in a vertical direction and care is taken to avoid any contact between the test pieces. After immersion, for 24 hours the test piece is removed from the water and kept for few minutes so that the excess water is drained off. Subsequently, the marked point is measured from the initially marked point so as to take a reading of the final thickness.

Figure 2.5: Thickness Swelling test sample

The proportional difference in mass (W) and thickness swelling (S) of the test piece were determined based on the mass difference and thickness difference by using the following equations 7 and 8:

$$W = \frac{w2-w1}{w1} \times 100\%, \quad (7)$$

w_1 is the initial mass of the test piece(g), before submerging;

w_2 is the final mass of the test specimen (g), after submerging.

$$S = \frac{s2-s1}{s1} \times 100\%, \quad (8)$$

s_1 is the mean value of the initial thickness of the test piece (mm) immersion in water;

s_2 is the mean value of the final thickness of the test piece (mm) after immersion in water.

2.3.2 Determination of Air Permeability Test

This sample was tested as per the standard EN 12114:2000. This test aims to determine the application of materials as insulation material and its vulnerability to the leakage of air. The resistance of airflow in the material is determined by passing the pressured air through the test rig to the materials. The test sample used for this test is a square of 100mm on each side. Before testing the samples, the specimen is wrapped up from the edges with a distinct air permeability adhesive tape called seal flex.

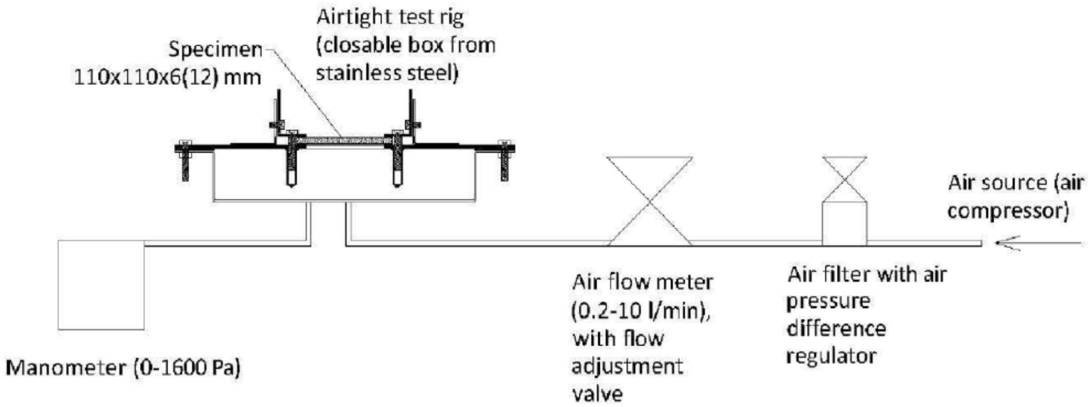

Figure 2.6 Schematic diagram of air permeability test rig. Source: (Villu K., 2016).

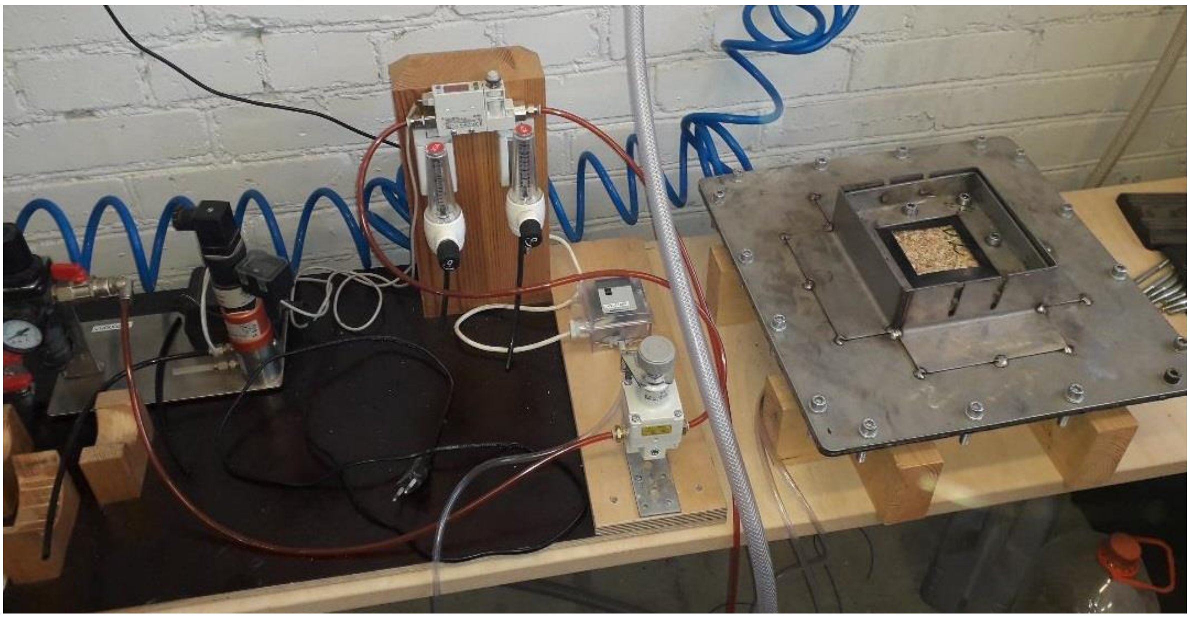

Figure 2.7 Air permeability test rig

The pressure was generated and transferred through a tube to the base of the equipment where the tested material is located. The maximum pressure administered was 550 Pa while the minimum pressure is 50 Pa. The pressure was administered thrice and maintained for 2 minutes. While some specimens can be airtight at maximum pressure, the other materials can have some leakage. Additional testing will be needed for any material that leaked air and the pressure will be varied 550, 425, 277, 181, 118, 77 and 50 Pa in other to determine the airflow of the material. Whenever samples are impermeable at 550 Pa (Stage 1) no further testing was required.

2.3.3 Determination of the Resistance to Axial Withdrawal of Screws

This experiment measures the resistance of the material to face withdrawal of screws by using a definite amount of force measured in Newtons (N) to extract a specific screw from the sample. 10 samples were taken from each material. The samples have a dimension of 65 mm × 50 mm. Subsequently, the screws were driven into the sample perpendicular to the surface of the test piece, which is positioned at the middle of the face of the test piece. In this experiment, a metallic screw with dimension 4.2 mm × 45 mm was used. The screws were thrust into the test pieces in such a way that 15 ± 0.5 mm of the entire thread was inserted in the sample as specified by the standard. In order to test a face screw holding the sample for a thickness lower than 15mm, it is important to insert the screw in a way that the incomplete thread sticks out to the opposite side of the test piece. The samples were attached to an electromechanical universal testing system Intron 5688 machine. A metal jig was used because the thickness of the sample was lower than the 15mm. To mount the test piece, the screw is inserted into the hole in the centre of the metal jig. An increasing axial load was applied to the underside of the screw head. The maximum load was recorded to the nearest 10 N.

2.3.4 Determination of Density

Density is a measure of the mass in relation to the volume of a given sample. With respect to the international standard EVS-EN 326, 5 samples of each materials measuring 50mm x 50mm were used. It was important that the specimen's dimension is determined using a sliding caliper to an accuracy of 0.01mm. The test piece should be weighed to an accuracy of 0.01g. Eventually, the volume of the samples should be calculated by multiplying the width by height and length. As a final point, the density of the material will be calculated in gramme per cubic millimetres (g/mm^3) and converted to a kilogram per cubic metre (kg/m^3).

3. RESULTS AND DISCUSSION

3.1 Density

The wood particleboard made with urea formaldehyde is the densest among all the material compared. The wood particleboard has a density of about 580kg/m^3 yielded the highest density while the Hemp hurd bonded with Soyad CA1025 yielded the lowest density with 477 kg/m^3. In comparing the density of the Soyad resins to the Acrodur resins with hemp hurd, Soyad has an average density of 502 kg/m^3 while Acrodur has an average density of 489 kg/m^3 as can be seen in figure 3.4.

The density of wood mixed with UF is slightly greater than that of Hemp hurd with UF resin which might be attributed to the wood's moisture content of 8% compared to hemp at 7%. The disparity between the average density of wood particleboard at 580 kg/m^3 is comparatively greater than that of hemp hurdboard at 510 kg/m^3.

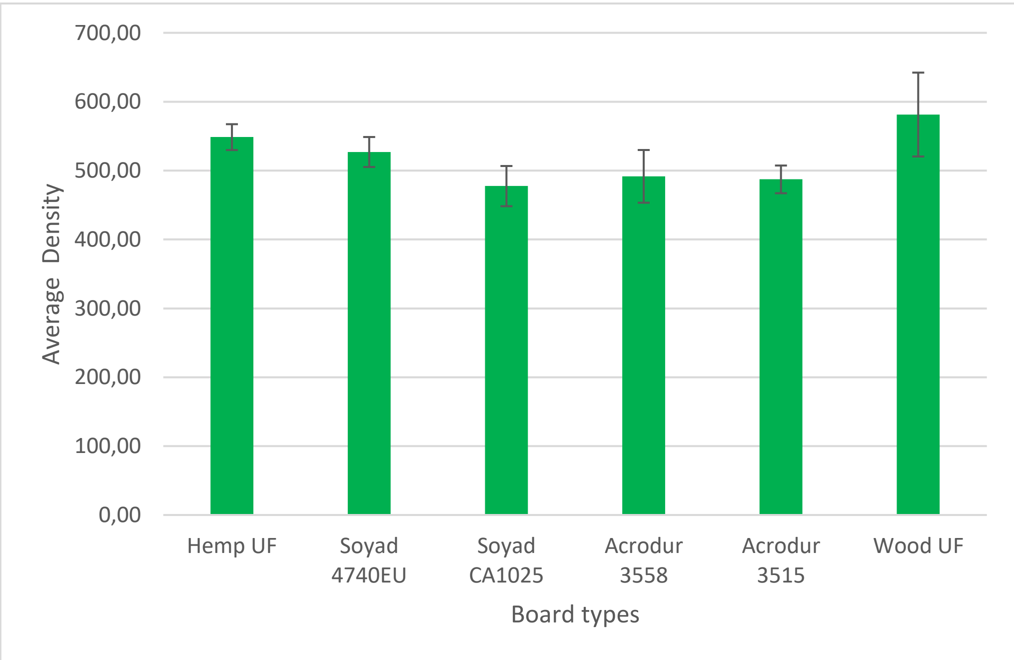

Figure 2.8 Density profile of the particleboard

As observed by (Heikko et. al., 2018), The hemp particleboard had a lower density when compared to wood particleboard as the spongy structure of hemp particle usually makes it possible for the adhesives to fill up the cavities thereby resulting in an overall lower density of the hurdboard. The density of the boards follows a comparable tendency, as the materials with the same glue category might have different density based on the physical and chemical properties of the resin and its pressing parameter. It is imperative to note that Soyad CA 1025 might have the lowest density because of different factors such as the amount of solid content in the resin and the preparation of the resin which might involve the addition of water which will eventually be lost through evaporation during pressing, thereby leaving the material less dense.

While there is currently limited literature regarding the density of hemp hurd bonded with Acrodur and Soyad resin, (S.A Sam-Brew, 2017) calculated the density of a 3 layered hemp hurd bonded with Acrodur 950L which is another product from BASF as having an average density of 569 kg/m^3 which is not significantly different to that of Acrodur 3515 and 3558 considering they are only 1-layered particleboard. However, according to (Lapyote P., Kaichang L.,2010), the soy-based adhesive reduced the density of the wood particleboard, from 640 kg/m^3 to 540 which might have affected the decrease of the density of hemp hurdboard glued with Soyad resin.

Comparing the values with that of (Li, X. et al., 2014), the density of hemp hurdboard in the literature was 540kg/m^3 which has no significant difference to that of this thesis. Hemp hurdboard has shown to be comparatively lightweight and less dense than wood. The low density of hemp hurdboard provides a good interface for mixing with the glue used for effective bonding.

3.2 Thickness Swelling and Water Absorption

The test result shows a whole submerging of the testpiece in water for a period of 24 hours. According to the standard test, a duration of 24 hours is required for this test. After 24 hours of immersion, the hemp hurdboards all increased in thickness and dimension. The average thickness swelling of the hemp hurdboard was 38.5% and its average water absorption was 162.8% while the average thickness swelling of the wood particleboard is 23% and the water absorption is 143%. The hemp hurdboard bonded with Acrodur resin shows a quite high water absorption and thickness swelling averaging about 162% in water absorption. (Heikko et al., 2017) revealed that the porous structure of the hemp particle might cause the hurdboard to be prone to water absorption and thickness swelling. The study showed that hemp hurdboard exhibited increased thickness swelling and water absorption than wood particleboard.

The statement above corresponds with the chart shown in figure 3.5, as the hemp hurdboard significantly have an increased level of water absorption and thickness swelling with comparison to that of wood particleboard.

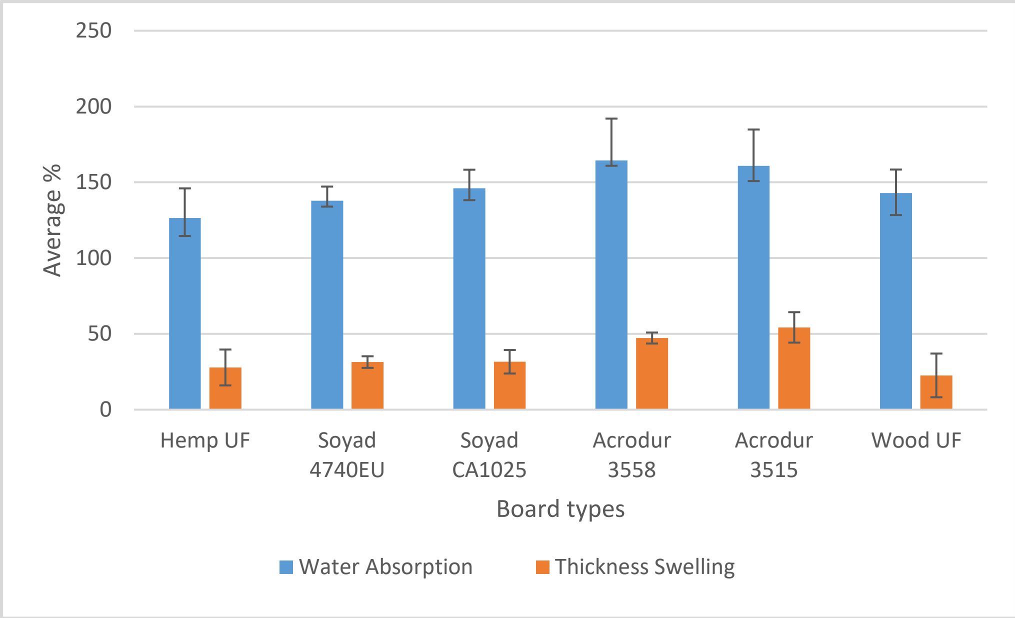

Figure 2.9 Water Absorption and Thickness Swelling profile of the particleboard

Twenty-four hours thickness swelling values of 27% was reported by (Sam-Brew S.A., 2017) for 550 kg/m^3 hemp hurd particleboards bonded with 10% UF resin while this research shows a 27% thickness swelling for 550 kg/m^3 hemp hurdboard bonded with 11% UF resin. For the same period, the hemp hurdboard bonded with Soyad resin showed no significant changes in the thickness swelling and water absorption which could be attributed to the resin used.

The wood particleboard bonded with Uf shows a significantly higher water absorption when compared to hemp hurdboard bonded with UF as there is a 12% increase in water absorption. However, the thickness swelling is quite opposite in which shows the hemp hurdboard have a higher swelling.

3.3 Resistance to Axial Withdrawal of Screws

The graph in figure 3.0 illustrates the resistance of the materials to the axial withdrawal of screws. The graphs show that the hemp hurdboard samples bonded with Soyad adhesive were the most resistant ones while the wood particleboard samples glued with UF adhesive proofed otherwise. From the graph, the hemp hurdboard glued with Soyad CA1025 has a resistance axial withdrawal 20.5 N/mm. Unlike the data from (Heikko et al., 2017), there was a significantly low value of 13N/mm and 11N/mm of hemp hurdboard bonded with UF and wood particleboard bonded with UF respectively. The data from (Heikko et. al., 2017) shows that the axial withdrawal of the screw of hemp hurdboard and wood particleboard is 37 N/mm and 47 N/mm respectively.

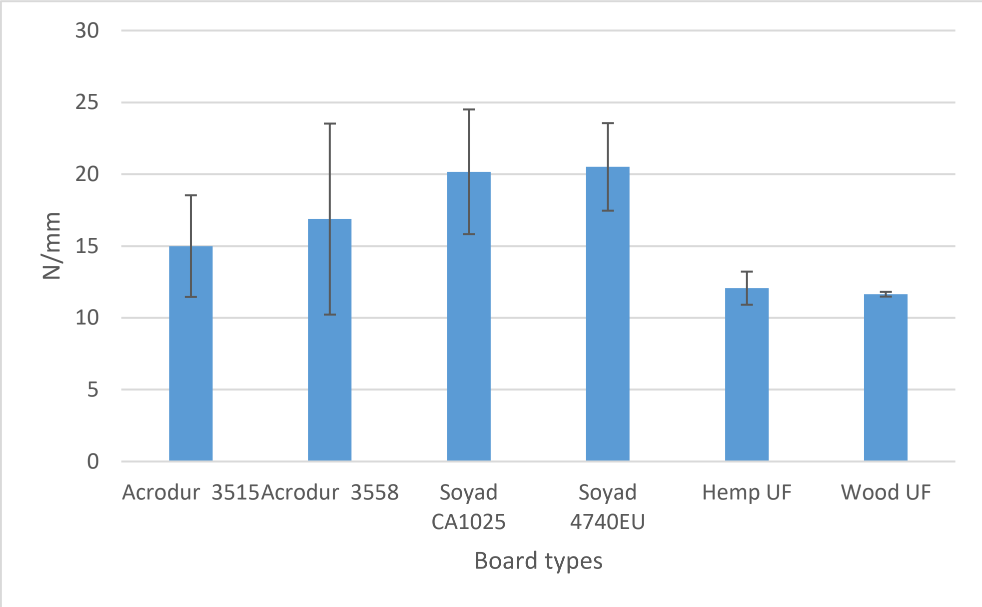

Figure 3.0 Resistance of axial withdrawal of screw to different materials.

The hemp hurdboard bonded with Acrodur resin showed an average resistance to axial withdrawal of screw of an average of 16N/mm. However, Acrodur 3558 showed a better resistance of withdrawal of screw of about 17N/mm.

3.4 Flexural Strength

The behaviour of the bending strength of different boards is shown in Figure 3.1. From the graph, if can be seen that hemp hurdboard glued with Soyad 4740EU resin is the strongest material with a maximum bending strength of 13.5Mpa and Modulus of elasticity of 490.95 Mpa as shown in figure 3.8. The wood particleboard has a mean modulus of elasticity of 650.50 MPa while its flexural strength was 2.3 MPa which is 17% value of hemp hurdboard glued with Soyad 4740EU resin. While the Modulus of elasticity compares with the value (Heikko et. al., 2018) good while its bending strength differs by 4.1 MPa. The average bending modulus of elasticity of hemp hurdboard bonded with UF was 446.60 MPa, which is 47% lower than the wood particleboard bonded with UF.

The Soyad resin shows a comparatively excellent flexural strength as the average maximum flexural strength is 12Mpa which is quite higher than that of wood while its modulus of elasticity averages 476 MPa. The weakest of the hemp hurdboard is that which is bonded with Acrodur 3515 resins which have a modulus of elasticity of 354 MPa and its Maximum flexural strength is 5.70MPa. Hemp hurdboard glued with Acrodur 3558 resin has a modulus of elasticity of 331.27 MPa and maximum flexural strength of 4.49 MPa as there is no significant difference with the other Acrodur resin.

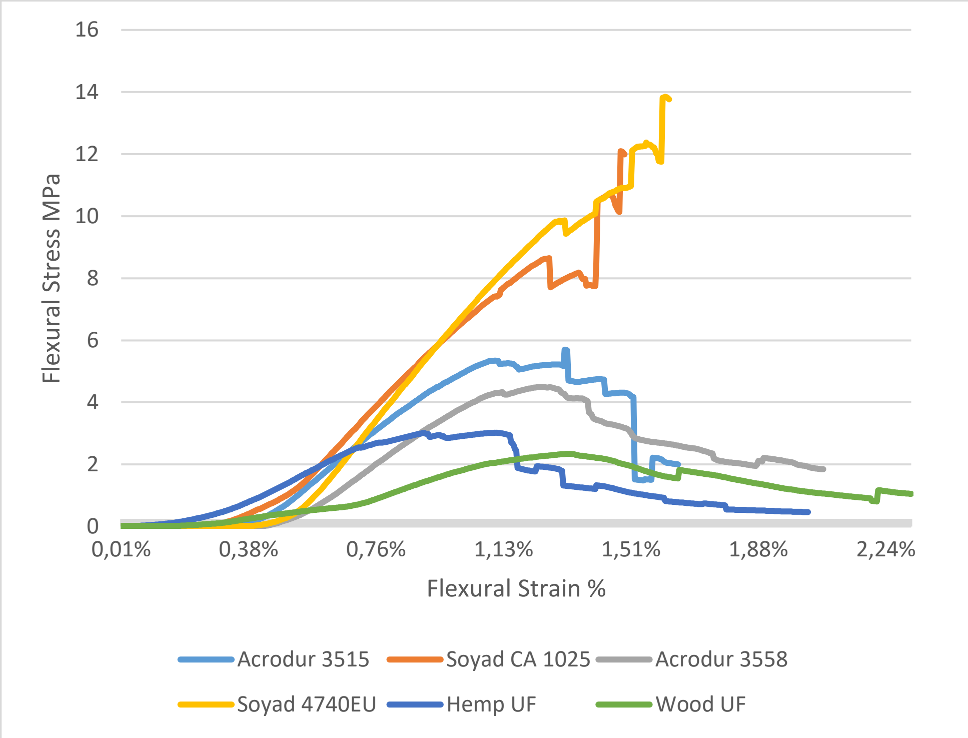

Figure 3.1 Flexural Strength profile of the particleboard

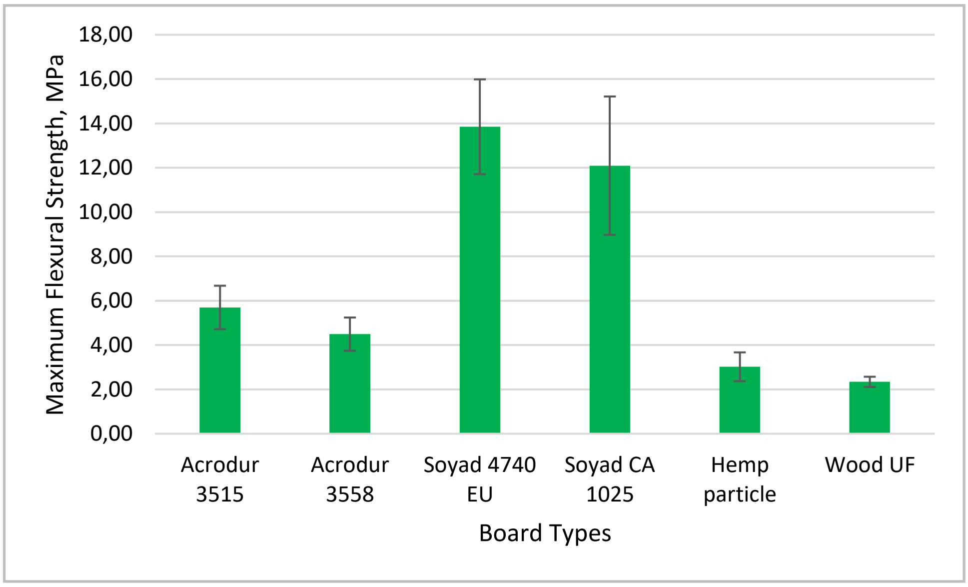

Figure 3.2 Maximum Flexural Strength profile of the particleboard

According to (Li, X. et al., 2014), the flexural strength of the hemp hurdboard with a density of 550Kg/m^3 was 5.63MPa which is significantly similar to that which has been represented in this thesis. However, the modulus of elasticity of the gotten from the article shows a 1.6GPa which is quite high when compared to the research undertaken in this thesis which might be due to the type of resin used and also the density of the composite.

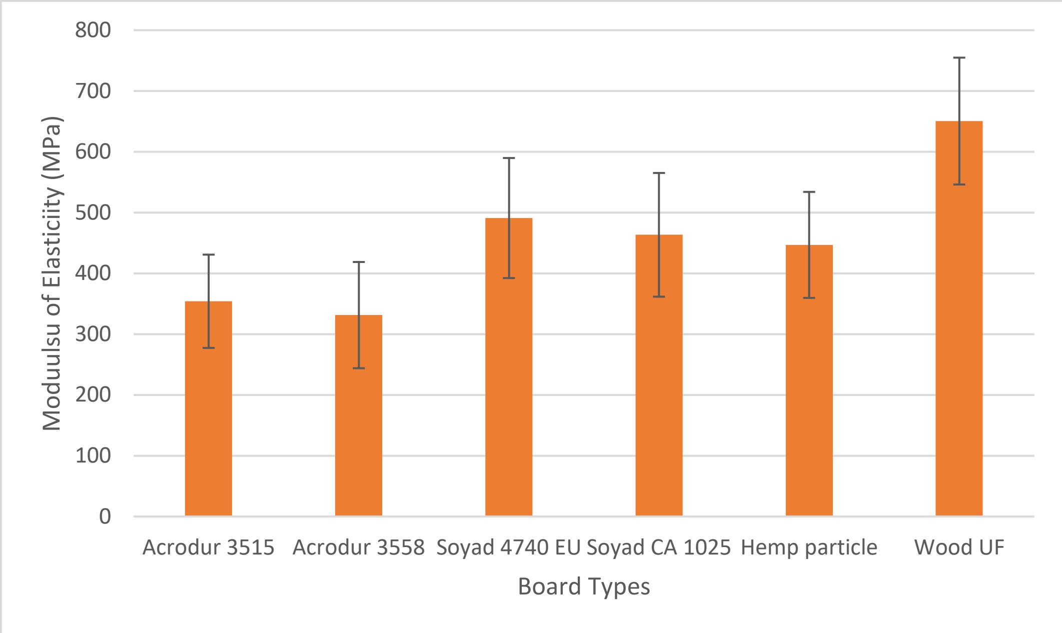

Figure 3.3 Modulus of Elasticity of the particleboard

3.5 Tensile Strength

The results shown in figure 3.4 illustrates the tensile strength of the materials perpendicular to the plane of the particleboard. The wood particleboard bonded with UF has a mean value of 0.2523 MPa while hemp hurdboard is 0.284 MPa. However, this result compares with the (Heikko et al., 2018) study that showed an elevated value of tensile strength of hemp hurdboard compared to the wood particleboard.

Moreover, the research shows that hemp hurdboard glued with Acrodur resin showed a higher tensile strength. The hemp hurdboard glued with Acrodur 3515 has a tensile strength of 0.284Mpa while that glued with Acrodur 3558 has a tensile strength of 0.208 MPa. Experimentally, hemp hurdboard bonded with the Soyad 4740EU has a mean value of the tensile strength of 0.37 MPa while the hemp hurdboard glued with Soyad CA1025 adhesive has a tensile strength of 0.3 MPa. The latter hurdboard may have had a lesser tensile strength because of the increased water content added to the resin before it was mixed with the hurds.

Hemp hurdboard demonstrated an increased tensile strength perpendicular to the plane of the board than that of the wood particleboards. The difference in the tensile strength proves that the adhesives are uniformly distributed in the hemp hurdboards compared to the wood particleboards.

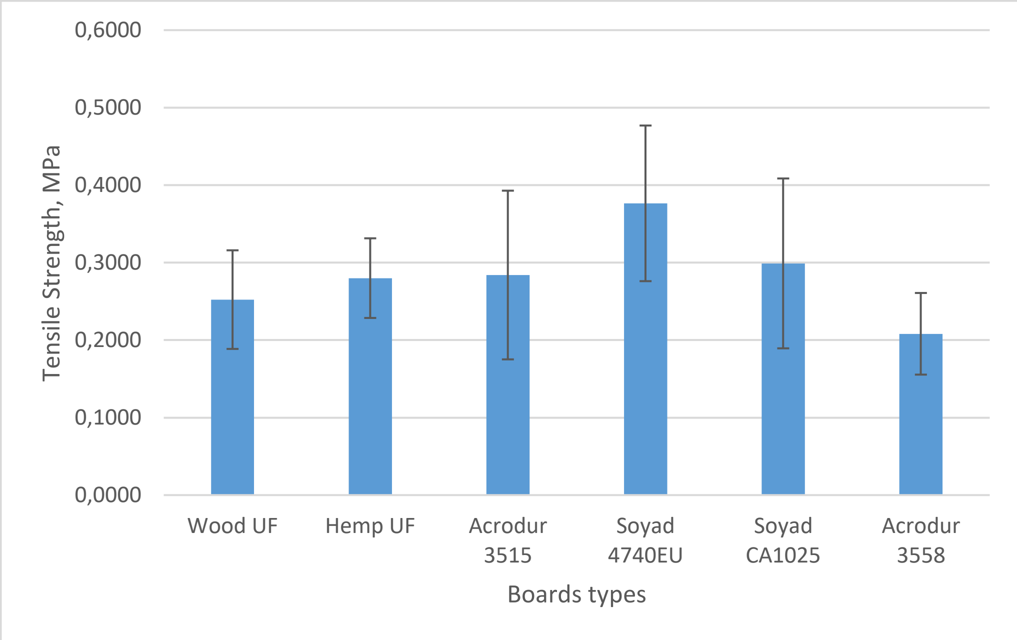

Figure 3.4 Tensile Strength profile of the particleboard

(Ndububa, E., 2015) show an average tensile strength of the particleboards to be 0.35MPa which is in tandem to the hemp hurdboard glued with Soyad 4740EU resin. However, it also imperative to point out that the EN 312 standard shows that the minimum tensile strength that a board should have should be 0.24 MPa. Almost all the boards passed the standard requirement except the board glued with Acrodur 3558 resin. (Lubi C. M & Thachil E.T. 2007) highlights its particleboard as having a tensile strength of 0.3 – 1.0 MPa which is significantly close to what was the thesis result.

3.6 Air Permeability

In this study, 5 types of particleboard were tested with 3 samples each. The board tested were subjected to a different level of pressure so as to determine if air passed through them. All of the hemp board were airtight showing no signs of the passage of air up to 550 Pa but the wood particleboard allowed air to pass through it as seen from the figure 3.5 below. The particle size of the hemp hurd might have been responsible for the particleboard not leaking air. It might also be that the soy flour might have helped to block the pores so as not to allow the Soy-based hemp hurdboard to leak air. Wood particleboards have a mean value of 1.84 L/(s·m2) which (Heikko et. al., 2018) highlights as 1.73 L/(s·m2). It was highlighted that the lower air permeability of hemp particleboard may be because of the interfacial fiber of the hurds which might lead to a better glue distribution in the board thereby making it airtight.

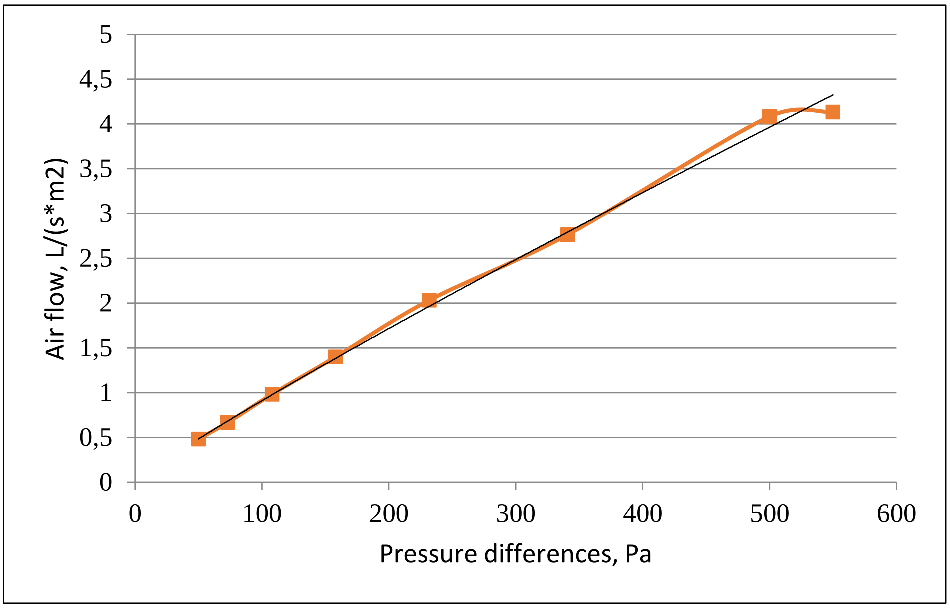

Figure 3.5 Air Permeability of wood particleboard

CONCLUSION

The aim of this master thesis is to develop hemp hurdboard from formaldehyde-free resin. In this master's thesis, particleboards are manufactured with hemp hurds and are bonded with environmentally-friendly adhesives. The boards are now tested in order to determine its properties in relation to traditional wood particleboard. Based on this study this is my conclusions:

1. The hemp hurdboard bonded with the soy-based adhesive exhibited the highest mechanical properties in resistance to axial withdrawal of screw, tensile strength and flexural strength. The average tensile strength and flexural strength exhibited by the soy-based hurdboard surpasses that of wood and other hurdboards.
2. The airtightness performance was also higher for the hemp hurdboards with increased pressure of 550 Pa unlike that of wood particleboard where air leakages were observed at 50 Pa. Although there is a need to compare the airtightness result shown by the hemp hurdboard with the conventional insulation material, it may be concluded that it is a suitable alternative to wood particleboard in this regard.
3. Hemp fibres compared to the wood fibres tend to be less dense and more porous, providing an avenue for the glue to flow within the particles to fill up the gaps. This could have further enhanced the airflow resistivity of the material.
4. The hemp hurdboards glued with Acrodur resins exhibited high water absorption and thickness swelling which may due to the increased hydrophilic properties of the board as a result of the acrodur being water based. However, the hemp hurdboard and wood particleboard glued with UF exhibited the lowest water absorption because of the water-resistant nature of the UF resin.
5. The hemp hurdboard glued with Soyad 4740EU adhesive demonstrated the best overall properties.

SUMMARY

Particleboards have been manufactured over the century using wood particles and UF as the adhesive. However, because of the impact of formaldehyde emission on human health, it is imperative to find alternative sustainable materials and environmentally friendly resin.

The aim of this master thesis is to develop hemp hurdboard from formaldehyde-free resin. In this master's thesis, there is a comparison between the properties of hemp hurdboard bonded with formaldehyde-free resins and the traditional particleboard (wood particleboard).

Hemp hurdboard was manufactured using formaldehyde-free resins such as Acrodur resins and Soyad™ resin which is a soy-based resin. Afterward, the board was tested so as to ascertain its flexural strength, tensile strength, resistance to axial withdrawal of screw and water absorption.

Based on the test results, the hemp hurdboard bonded with the soy-based adhesive exhibited the highest mechanical properties in resistance to axial withdrawal of screw, tensile strength and flexural strength.

The hemp hurdboard exhibited excellent airtightness compared to the wood particleboard and could be used as an insulation material for buildings. All the samples of the hemp hurdboard were airtight while the wood particleboard leaked at 50 Pa.

The hemp hurdboards bonded with Soyad 4740 resin exhibited the best overall properties and since they are formaldehyde-free, they may be applied in in-house insulation and in furniture manufacturing because of the non-emission of volatile organic compounds (VOC). But, further research is required to investigate the suitability of this material as an insulation material.

KOKKUVÕTE

Puitlaastplaatide valmistamise tehnoloogia puidulaastudest ja karbamiidliimist on juba üle sajandi vana. Sellisel meetodil valmistatud plaatidel tekib formaldehüüdi emissioon keskkonda, mis kahjustab inimeste tervist. Seetõttu on oluline leida loodussõbraliku vaigu baasil alternatiiv olemasolevale karbamiidliimi tehnoloogiale.

Magistritöö eesmärgiks on välja arendada formaldehüüdivabade liimide baasil kanepiuuplaadid. Töös võrreldakse kanepiluuplaate traditsiooniliste puitlaastplaatidega. Töös valmistatakse kanepiluuplaadid akrüülvaiguga (Acrodur) ja sojapõhise vaiguga (Soyad). Seejärel katsetatakse plaatide mehaanilisi omadusi ja määratakse kindlaks paindetugevus, pinnaga ristsuunaline tõmbetugevus, vastupanu kruviväljatõmbele ning lisaks veeimavus ja pundumine.

Katsete tulemused näitasid, et sojapõhise liimiga valmistatud kanepiluuplaat andis kõige kõrgemad mehaanilised omadused kruvide väljatõmbe vastupanule, paindetugevusele ja pinnaga ristisuunalisele tõmbetugevusele. Kõik kanepiluuplaadid näitasid suurepärast õhupidavust ja on seega sobilikud kasutamiseks isolatsiooniplaadina.

Kõige paremaid omadusi andis Soyad 4740 vaiguga valmistatud kanepiluuplaadid ning kuna need on ka formaldehüüdivabad ja ei eralda lenduvaid orgaanilisi ühendeid (VOC), siis on neid võimalik edukalt kasutada majasiseseks isolatsioonimaterjaliks ja ka mööblivalmistamiseks. Antud töö annab hea aluse edasisteks uurimustöödeks nende materjalide kasutamiseks isolatsioonimaterjalina.

LIST OF REFERENCES

Bo M., (2004).Properties of Plant Fibre Yarn Polymer Composites an Experimental Study. - Report Technical University of Denmark. 75, 28–38. Science Direct (30.03.2018).

Dinesh B. & Anagha S., (2014). CNSL: An environment friendly alternative for the modern coating industry. Journal of Coatings Technology and Research. 11. 10.1007/s11998-013-9521-3.

Hamarneh, A. I. M. (2010). Novel wood adhesives from bio-based materials and polyketones. Groningen: s.n. (08.012.2018).

Kallakas H., Närep M, Närep A., Poltimäe T., Kers J. (2018) Mechanical and physical properties of industrial hemp-based insulation materials. Prodeeding of the Estonian Academy of Science. 2018. (30.05.2019).

Jeong-Hun L., Jisoo J., Sumin K. (2011).Green Adhesives Using Tannin and Cashew Nut Shell Liquid for Environment-friendly Furniture Materials. Journal of Korean Furniture Society,22(3),219-229. (02.07.2019).

Khalfallah M., Abbès B., Abbès F., Guo Y.Q., Marcel V., Duval A., Vanfleteren F., Rousseau Innovative F. (2014) flax tapes reinforced Acrodur biocomposites: A new alternative forautomotive applications. Journal of Materials and Design Volume 64, 116–126. (30.12.2016).

Khazaeian A., Ashori A., Dizaj M.Y., (2015) Suitability of sorghum stalk fiber of production of particleboard. Journal of Carbohydrate Polymer 2015, Apr 20; 120:15-21 (11. 11. 2018).

Kozlowski, R., Helwig, M., (1998). Lignocellulosic polymer composite. In: Prasad, P.N. (Ed.), Science and Technology of Polymers and Advanced Materials. Plenum Press, New York, pp. 679/698. (21. 09.2018).

Lapyote P., Kaichang L.,(2010). A new method of making particleboard with a formaldehyde-free soy-based adhesive, Composites Part A: Applied Science and Manufacturing, Volume 41, Issue 10, 2010, Pages 1447-1453, ISSN 1359-835X.

Lee, J.-H., Kim, J., Kim, S., & Kim, J. T. (2013). Characteristics of Particleboards Using Tannin Resin as Novel Environment-Friendly Adhesion System. Indoor and Built Environment, 22(1), 61–67. https://doi.org/10.1177/1420326X12469552. Sage Journal (30.03.2018).

Lilholt H., Lawther J. M. (2000). Journal of Natural Organic Fibers. - Comprehensive Composite Materials Volume 1, 303-325. Science Direct (12.01.2019).

Li, Xiaoping & Wang, Siqun & Du, Guanben & Wu, Zhangkang & Gong, Yingchun. (2014). Manufacturing Particleboard Using Hemp Shiv and Wood Particles with Low Free Formaldehyde Emission Urea-Formaldehyde Resin. Forest Products Journal. 64. 187-191. 10.13073/FPJ-D-13-00073.

Lubi C. M. & Thachil E.T., (2007) Particleboard from Cashew Nut Shell Liquid, Polymer-Plastics Technology and Engineering, 46:4, 393-400, DOI: 10.1080/03602550701242893

Nairong Chen ID , Peitao Zheng , Qinzhi Zeng , Qiaojia Lin and Jiuping Rao (2017). Characterization and Performance of Soy-Based Adhesives Cured with Epoxy Resin. Journal of Polymers 2017, 9, 514; doi:10.3390/polym9100514 (08.02.2019).

Pickering K.L., G.W. Beckermann, S.N. Alam, N.J. Foreman, (2007). Optimizing industrial hemp fibre for composites. Composites Part A: Applied Science and Manufacturing. Volume 38, Issue 2, February 461–468. Science Direct (15.11.2016).

Roy, A.K. & Sardar, Dhiraj & Sen, S.K.. (1989). Jute stick lignin-based adhesives for particle boards. Biological Wastes. 27. 63–66. 10.1016/0269-7483(89)90030-X. (02.09.2018).

Sgriccia N., Hawley M.C., Misra M. (2008). Characterization of natural fiber surfaces and natural fiber composites. - Composites Part A: Applied Science and Manufacturing, 39, 1632–1637. (15.07. 2018).

Shahzad, A. (2012). Hemp fiber and its composites – a review. Journal of Composite Materials, 46(8), 973–986. https://doi.org/10.1177/0021998311413623. Sage Journal (18.09.2018).

Silva, Diogo & Rocco Lahr, Francisco & Varanda, Luciano & Christoforo, André & Ometto, Aldo. (2015). Environmental performance assessment of the melamine-urea-formaldehyde (MUF) resin manufacture: A case study in Brazil. Journal of Cleaner Production. 96. 299-307. 10.1016/j.jclepro.2014.03.007 (01.12.2018).

Sam-Brew, S.A. (2017). The use of flax and hemp resource for particleboard (T). University of British Columbia. Retrieved from https:open.library.ubc.ca/collections/ubctheses/24/items/1.0342816 (02.02.2019).

Sullins, Theresa & Pillay, Selvum & Komus, Alastair & Ning, Haibin. (2017). Hemp fiber reinforced polypropylene composites: The effects of material treatments. Composites Part B: Engineering. 114. 10.1016/j.compositesb.2017.02.001. (03.06.2018).

Thygesen.A (2006). Properties of hemp fibre polymer composites - An optimisation of fibre properties using novel defibration methods and fibre characterization. - Risø-PhD; No. 11(EN). (02.02.2019) (03.06.2018).

Villu Kukk. (2016). Impact of cracks to the hygrothermal performance of cross laminated timber, Master's thesis – Tallinn university of technology, Estonia. Research paper (12.08.2018).

Wang, D., Sun, X.S., (2002). Low density particleboard from wheat straw and corn pith. Ind. Crops Prod. 15(1), 47/50. (02.09.2018).

APPENDIX 1 Air Permeability Test Result

Table 1.7: Air Pearmeablility of wood particleboard and hemp hurdboards

Samples	Calculated Pressure	Wood UF (l/min)	Hemp UF	Acrodur 3515	Acrodur 3558	Soyad CA 1025	Soyad 4740EU
1	50	0,28	Air tight	Air tight	Air tight	Air tight	Air tight
2		0,29					
3		0,31					
1	73	0,40	Air tight	Air tight	Air tight	Air tight	Air tight
2		0,40					
3		0,42					
1	108	0,56	Air tight	Air tight	Air tight	Air tight	Air tight
2		0,56					
3		0,56					
1	158	0,82	Air tight	Air tight	Air tight	Air tight	Air tight
2		0,84					
3		0,83					
1	232	1,12	Air tight	Air tight	Air tight	Air tight	Air tight
2		1,10					
3		1,14					
1	341	1,66	Air tight	Air tight	Air tight	Air tight	Air tight
2		1,67					
3		1,64					
1	500	2,44	Air tight	Air tight	Air tight	Air tight	Air tight
2		2,46					
3		2,47					
1	550	2,67	Air tight	Air tight	Air tight	Air tight	Air tight
2		2,68					
3		2,67					

Table 1.8: Air Pearmeablility of wood particleboard

Pressure step	**Pressure, Pa**	**Average Air permeability (L/min)**	**Air flow l/(s*m2)**
0	50	0,29	0,48
1	73	0,41	0,67
2	108	0,56	0,98
3	158	0,82	1,40
4	232	1,12	2,03
5	341	1,66	2,77
6	500	2,45	4,08
7	550	2,67	4,13

APPENDIX 2 Density Result

Figure 1.9 Density of Hemp hurdboard with UF resin

Resin	Density	Mass (g)	vol (mm)
UF1	0,000579286	23,04	39773,09
UF2	0,000549011	22,79	41511,03
UF3	0,000528169	18,83	35651,45
UF4	0,000529663	22,08	41686,87
UF5	0,000550566	20,86	37888,31
UF6	0,000554892	22,16	39935,68

Figure 2.0 Density of Wood Particleboard with UF resin

Resin	Density	Mass (g)	vol (mm)
W1	0,000538	18,79	34905,78
W2	0,000624	24,12	38629,00
W3	0,000594	19,83	35651,45
W4	0,000596	21,08	41686,87
W5	0,000614	20,86	37288,31
W6	0,000598	20,16	37435,60

Figure 2.1 Density of Hemp hurdboard with Soyad 4740EU resin

Resin	Density	Mass(g)	vol (mm)
SY1	0,000543	20,07	36987,88
SY2	0,000504	18,17	36063,06
SY3	0,000556	19,96	35884,41
SY4	0,000512	18,40	35937,67
SY5	0,000521	19,47	37354,35
SY6	0,000546	20,27	36487,81

Figure 2.2 Density of Hemp hurdboard with Soyad CA1025 resin

Resin	Density	Mass(g)	vol (mm)
W1	0,000538	18,79	34905,78
W2	0,000624	24,12	38629,00
W3	0,000594	19,83	35651,45
W4	0,000596	21,08	41686,87
W5	0,000614	20,86	37288,31
W6	0,000598	20,16	37435,60

Figure 2.3 Density of Hemp hurdboard with Acrodur 3515 resin

Resin	Density	mass	vol (mm)
AD1	0,00046	17,30	37606,48
AD2	0,000492	20,22	41069,63
AD3	0,000488	18,55	37999,69
AD4	0,000516	19,80	38405,4
AD5	0,00048	18,00	37483,67
AD6	0,00045	18,15	37506,28

Figure 2.4 Density of Hemp hurdboard with Acrodur 3558 resin

Resin	Density	Mass (g)	vol (mm)
AE1	0,00053	18,79	35422,51
AE2	0,000443	15,50	34966,88
AE3	0,000443	16,22	36594,92
AE4	0,000514	19,09	37105,33
AE5	0,000509	18,02	35373,09
AE6	0,000509	18,34	36042,06

Table 2.5: Density profile for wood particleboard and hemp hurdboards

Boards Types	Average Density	Standard Deviation
Hemp UF	548,60	18,77
Soyad 4740EU	527,00	21,75
Soyad CA1025	477,47	29,19
Acrodur 3558	491,62	38,27
Acrodur 3515	487,26	20,11
Wood UF	581,35	60,88

APPENDIX 3 Axial Withdrawal of Screw Test Result

Table 2.6: Average Resistance to Axial Withdrawal of Screw for wood particleboard and hemp hurdboard

Sample	Acrodur 3515 (N/mm)	Acrodur 3558 (N/mm)	Soyad CA1025 (N/mm)	Soyad 4740EU (N/mm)	Hemp UF (N/mm)	Wood UF (N/mm)
1	9,81	27,25	18,56	16,78	12.88	11,66
2	12,34	19,11	19,16	18,2	11.65	11,47
3	16,94	11,03	11,56	22,34	11.25	11,8
4	18,6	17,01	24,81	17,6	13,65	10,65
5	16,6	11,07	23,83	18,83	15,97	12,12
6	13,03	18,01	21,5	21,98	10,54	11,33
7	13,19	12,76	19,39	23,1	10,78	11,98
8	15,32	14,76	20,93	25,23	11,12	10,65
Average	**14,99**	**16,8**	**20,17**	**20,51**	**12,07**	**11,6**
Stdv	**3,54**	**6,65**	**4,34**	**3,05**	**1,15**	**0,17**

APPENDIX 4 Thickness Swelling and Water Absorption Result

Figure 2.7 Water Absorption and Thickness Swelling for hemp hurdboard bonded with UF

Specimen	WA (%)	TS (%)
UF1	101,13	14,15
UF2	123,26	18,76
UF3	136,62	43,96
UF4	134,69	25,62
UF5	154,03	35,49
UF6	118,37	15,44

Figure 2.8 Water Absorption and Thickness Swelling for hemp hurdboard bonded with Soyad 4740EU resin

Specimen	WA (%)	TS (%)
SY1	127,01	26,26
SY2	139,68	35,21
SY3	136,97	32,25
SY4	152,28	34,60
SY5	133,13	28,74
SY6	121,01	25,46

Figure 2.9 Water Absorption and Thickness Swelling for hemp hurdboard bonded with Soyad CA1025 resin

Specimen	WA (%)	TS (%)
SD1	151,02	39,77
SD2	162,08	32,91
SD3	148,23	38,16
SD4	129,60	24,08
SD5	139,07	23,13
SD6	141,02	39,77

Figure 3.0 Water Absorption and Thickness Swelling for hemp hurdboard bonded with Acrodur 3558

Specimen	WA (%)	TS (%)
AE1	135,50	33,07
AE2	167,81	47,01
AE3	162,82	46,18
AE4	188,95	50,88
AE5	151,91	50,36
AE6	174,21	41,91

Figure 3.1 Water Absorption and Thickness Swelling for hemp hurdboard bonded with Acrodur 3515 resin

Specimen	WA (%)	TS (%)
AD1	232,77	61,66
AD2	168,84	44,06
AD3	185,55	42,93
AD4	186,16	64,11
AD5	167,33	58,67
AD6	175,77	61,66

Figure 3.2 Water Absorption and Thickness Swelling for wood particleboard bonded with UF

Specimen	WA (%)	TS (%)
W1	120,22	28,41
W2	159,04	50,81
W3	131,22	12,41
W4	149,04	39,81
W5	120,22	43,41
W6	159,04	46,81

Figure 3.3 Average Water Absorption and Thickness Swelling for Particleboard and Hurdboard

Sample	**Avg. % Increase in wt.**	**Avg. % increase in dimension**	**Stdev. of WA**	**Stdev. Of TS**
Hemp UF	126.39	27.85	19.65	11.82577
Soyad 4740EU	137.81	31.41	9.39	3.839074
Soyad CA1025	146	31.61	12.31	7.746001
Acrodur 3558	164.54	47.27	27.51	3.623651
Acrodur 3515	160.88	54.29	23.96	10.04578
Wood UF	142.85	22.61	15.59	14.42631

APPENDIX 5 Tensile Strength Test Results

Figure 3.4 Tensile strength of Acrodur 3515 hemp hurdboard

Specimen	Maximum Load (N)	Tensile Strength (N/mm^2)
1	189,06	0,08
2	415,49	0,17
3	168,52	0,06
4	942,82	0,38
5	528,68	0,19
6	1047,40	0,42
7	617,27	0,28
8	712,89	0,31

Figure 3.5 Tensile strength of Acrodur 3558 hemp hurdboard

Specimen	Maximum Load (N)	Tensile Strength (N/mm^2)
1	634,43	0,26
2	618,41	0,25
3	241,87	0,09
4	314,10	0,13
5	295,78	0,12
6	396,05	0,16
7	471,58	0,19
8	563,26	0,23

Figure 3.6 Tensile strength of UF hemp hurdboard

Specimen	Maximum Load (N)	Tensile Strength (N/mm^2)
1	174,03	0,07
2	159,64	0,06
3	307,16	0,12
4	220,29	0,08
5	226,38	0,09
6	151,03	0,06
7	218,06	0,09
8	218,06	0,08

Figure 3.7 Tensile strength of Soyad CA1025 hemp hurdboard

Specimen	**Maximum Load (N)**	**Tensile Strength (N/mm^2)**
1	1187,62	0,48
2	857,36	0,34
3	556,79	0,22
4	558,02	ˇ0,23
5	664,00	0,27
6	1354,25	0,54
7	869,89	0,35
8	557,80	0,22

Figure 3.8 Tensile strength of Soyad 4740EU hemp hurdboard

Specimen	**Maximum Load (N)**	**Tensile Strength (N/mm^2)**
1	1025,25	0,48
2	731,94	0,29
3	1019,65	0,41
4	625,63	0,25
5	843,18	0,33
6	994,14	0,40
7	1353,76	0,54
8	1147,63	0,46

Figure 3.9 Tensile strength of UF Wood Particelboard

Specimen	**Maximum Load (N)**	**Tensile Strength (N/mm^2)**
1	447,08	0,18
2	120,89	0,05
3	725,08	0,29
4	684,25	0,23
5	664,00	0,22
6	425,63	0,17
7	558,14	0,21
8	557,80	0,22