Thermally modified mini-CLT panel

Anti-swelling efficiency and strength properties

LAB University of Applied Sciences
Bachelor of engineering, Wood Technology
2021
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Abstract

Author(s)	Publication type	Completion year
Palokangas, Johanna	Thesis, UAS	2021
	Number of pages	
	35	

Title of the thesis

Thermally modified mini-CLT panel

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Degree

Bachelor of Engineering, Wood Technology (UAS)

Name, title, and organization of the supervising teacher

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Name, title, and organization of the client

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Abstract

The purpose of the thesis project was to examine the anti-swelling efficiency (ASE), modulus of elasticity (MOE), and modulus of rupture (MOR) of the thermally modified mini-CLT panel. Thermally modified glulam and thermally modified solid timber were tested as control groups in ASE. MOE and MOR tests were implemented to mini-CLT and glulam. The tested mini-CLT panels were prototypes, and the commercial production starts in next few years. The project was commissioned by Abodo Wood Ltd. ASE tests were implemented at Abodo's facilities. MOE and MOR tests were implemented by a third party in material testing laboratory.

The theory section of the thesis consists of an introduction of Abodo, information about the radiata pine and forest plantations in New Zealand, thermal modification theory and process, and general information of the glulam and CLT manufacturing processes.

The preliminary expectation was that the mini-CLT would swell 0.5% in width wise, which was the main interest regarding testing. The test resulted in a 0.8% +/-0.1% swelling after 14 days immersion to water compared to oven dry width and 0.6% +/- 0.1% swelling compared to initial (5.7% MC) width. The mini-CLT swelled the most in thickness (5.4%), which was more than the thickness swelling in control groups.

In MOE and MOR the results regarding the mini-CLT were weak compared to the glulam. The weaker results were due to the orientation of the mini-CLT specimens, which were cut across the grain of the main layers of the board. Hence the mini-CLT panels were bended perpendicular to grain, whereas glulam was tested parallel to grain. Bending strength of wood is known to be significantly higher parallel to grain and therefore better results for mini-CLT are expected if the specimens were oriented parallel to grain in the main layers of the board.

Keywords

Mini-CLT panel, Glued laminated timber, Thermal modification, Radiata pine, Anti-swelling efficiency, Modulus of elasticity, Modulus of rupture

Contents

Appendix

1 Introduction

Wood is an organic, renewable material, which makes it special in the context of construction materials. Because it is organic, this means that every piece of wood is different. Only a certain kind of knot can lead to the rejection of a piece of wood or a board. Nevertheless, wood is one of the oldest building materials. As a material it faces some challenges, especially in contemporary times as buildings are bigger and higher, and construction is more regulated. The material should be as homogeneous as possible regarding the construction business, for it can be regarded reliable. Depending on the use, wood as a material can be exposed to, among others, heavy loads, moisture, pests, and harsh weather conditions.

Plain sawn timber in itself is not the most durable, but people have always been active to find new methods and treatments in order to make timber more durable. Some of the old methods have been developed further to industrial use such, as thermal modification and new modification methods are invented. Other modern, environmentally friendly modified wood products are foe example, Kebony Wood, in which wood is impregnated with furfuryl alcohol, and Accoya Wood which is chemically modified based on acetylation. In the Accoya process water is substituted with acetic anhydride. Also engineered wood products have been invented and developed to increase the possibilities of wood as building material. The most recent engineered wood product innovation is the Cross laminated Timber, which is already 25 years old. This describes well the long history of wood products and the relatively slow changes in the industry, as the newest product is quarter of a century old, and it is just recently that the utilising and demand have begun on a bigger scale.

The purpose of exterior cladding is to protect the building, but it also has a visual meaning. The biggest challenges for exterior cladding are weather conditions which cause dimension instability, cracking, and decay. As the wood product markets are global, also the products should be suitable to different kind of weather conditions. Higher rain levels, storms as well as heat and drought are to be taken into consideration.

The theory part of this thesis project consists of the introduction of the commissioner of the project, Abodo Wood Ltd., radiata pine as a species, the thermal modification treatment and engineered wood products, such as glued laminated timber (glulam) and cross laminated timber (CLT). The experimental part of the thesis project was to examinate the properties of the mini-CLT panel, Abodo’s new upcoming product, which will be in exterior cladding use. The mini-CLT panel is not yet in commercial production, but a few prototype panels have been made for testing. The tests that were implemented are anti-swelling efficiency, modulus of elasticity and bending strength. There were three groups in ASE tests: mini-CLT panel, glulam and thermally modified solid timber (solid TM). Glulam and mini-CLT were tested in bending for MOE and MOR. The test results are compared together, although the structures of the products are different and that is why not necessarily comparable. In addition, also test regarding weathering has been started for mini-CLT panel.

Expectations are that the CLT structure together with thermal modification treatment should give a very good result in dimension stability especially in width direction. The purpose of the testing is to find out how mini-CLT panel performs and if the results match to the expectations.

2 Abodo Wood

2.1 History

Abodo Wood is a family-owned New Zealander company founded by Daniel Gudsell in 2001. As he was traveling on the Pacific Islands, he noticed that eventually there would be a lack of timber due to the fast pace of harvesting of the local limited resources. Gudsell's business idea was to export radiata pine from New Zealand to the Pacific Islands. In a TEDxAuckland speech, Gudsell (2019) spoke about how it used to be normal to treat the timber with CCA (chromated copper arsenate) in New Zealand, when at the same time this treatment was already forbidden in many other countries due to health risks. Complaints regarding health problems caused by CCA timber led Gudsell to change the product to natural thermally modified timber.

2.2 Production

Abodo Wood acquires their wood from the Kaingaroa radiata pine forest plantation. The forest is sustainably taken care of, and it is FSC certificated. After harvesting, the wood is transported to the Donelley Sawmill which is located in the central North Island between two cities, Taupo, and Rotorua, right next to the Kaingaroa forest. The thermal modification process for the timber is carried out at the sawmill. Glue laminating, profiling and other processes if needed, are done by a third party before the timber arrives to the Abodo factory in Auckland. At Abodo's facilities the timber is either coated or packed and sent to a customer as uncoated. Abodo Wood is the only company in New Zealand that sells thermally modified timber. A large part of their products is sold overseas. (Gudsell, 2020.)

2.3 Abodo Wood as a business

Abodo Wood Ltd employs 45 people and the annual turnover is NZD60 million (Gudsell, 2021). Abodo has got a clear vision regarding the future of wood products and strong green values to manufacture long lasting and renewable building materials from sustainable forest sources. Company wants to offer the best and most durable cladding products to their customers. To achieve this goal, they invest time and money into research and look into new possibilities in terms of coatings but also structure wise.

Currently there are two thermal modifying chambers in use and a third one will be taken in use later in 2021. This will increase the capacity up to 1500m^3 per month. The construction of a new factory is also underway. That will increase the whole production capacity and give more flexibility into the production. The new factory will include glue laminating, band sawing to size and possible profiling. In addition, it will include a small press for the mini-CLT panels and a CNC machine for prototyping. (Gudsell, 2021.)

2.4 Products

Abodo Wood is focused on exterior cladding and decking products. They mainly use thermally modified radiata pine. Another wood species they use in the exterior cladding manufacture is untreated Douglas fir. Abodo's product range includes various kinds of vertically and horizontally installed profiles. The surface of the cladding boards is either band sawn or brush finished. Decking is available in two different profiles and in a couple different colours.

Abodo wood has their own protector oil for claddings. This protector oil is available in nine different colours. In addition, they sell Sioo:x coated cladding and charred cladding. Sioo:x is a silicon based natural coating product which protects wood from harsh weather conditions such as sun or snow, rot, mould, and termites. Sioo:x Wood coat is based on a patented silicon technology where wood protection and surface protection are combined together. (Sioo:x 2021.)

3 Exterior cladding

Purpose of the cladding

Exterior cladding has an important meaning in terms of protecting the building from various weather conditions. Rain and moisture cause most of the stress together with temperature changes and UV-radiation. Untreated timber changes dimensions from one to eight percent when it gets wet and dries again. (Heikkinen 2004, 33.) A thicker board is better coping with moisture and is less exposed to cracking and twisting. Centuries ago, cladding boards used to be 28-48mm thick. The thickness of cladding boards today can be as low as 16mm. (Soikkeli 2004, 36.)

Cladded wood can last from tens of years up to a hundred with appropriate protection and maintenance. Together with the visual aspect it is important to take a look how to protect wood from rain and moisture regarding architectural planning. (Heikkinen 2004, 34.) Cladding boards are usually fixed either horizontally or vertically. Manufacturers offer several profiles. Regarding a structural protection matter, it is important to leave a cap between the wall and cladding in order to ensure air circulation. Eaves cover the top of the cladding from the rain. The hight of the plinth should be at least 300mm, in order to ensure the bottom edge of the gladding is not too close to the ground. Joints and corners are other vulnerable parts. If not covered properly, water can access the wood. Water travels faster in the longitudinal grain direction of the board. Mouldings help water to drip out from the wood. (Soikkeli, 2004.)

4 Radiata pine

4.1 History of Radiata pine

Radiata Pine, *Pinus Radiata*, is originally from California, USA. It is also known as Monterey pine, pino insigne or remarkable pine (Mead 2013, 3). Today the radiata pine is rare in its native growth area in California. Estimations vary between 5 000 and 10 000 hectares. (Zander Associates 2002, Roger 2004, according to Mead 2013, 4.) Although it has become nearly extinct in California, it has been imported and planted around the World already during the late eighteenth century and early nineteenth century. David Douglas planted radiata pine to England in 1833 using seeds which were collected in 1830. After this, plantings have been recorded in Sydney and Melbourne, Australia since 1857 and some years later in Canterbury, New Zealand. (Mead 2013, 3-4.) In 1871 the first plantations were done in Uruguay, in 1885 near Cape Town in South-Africa (Donald 1993, according to Mead 2013, 4). In 1886 in Chile (Contesse 1987, according to Mead 2013, 4), and in Ecuador in 1905 (Mead, 2013, 4). Larger scale planting in Spain started in 1950's and the most recently radiata pine has been introduced to Sichuan Provance in China in 1990's. (Hui-guan & al. 2003, according to Mead 2013, 3-4).

According to Mead (2013, 6.) the development process from introducing the radiata pine to commercial use plantations can be divided to four phases. After the first "introduction" phase, the radiata pine was studied for decades and people started to understand its potential. The advantage of the radiata pine was, especially the fast growth.

The second phase Mead (2013, 6-8.) calls is "acceptance". The acceptation of the radiata pine as a plantation species happened faster in the Southern Hemisphere after colonization. For example, in New Zealand, the radiata pine was seen as a solution for a potential timber shortage in 1960's, as native trees were slow growing or otherwise unsuitable for timber usage. In Europe, the acceptance has started much later, because the common thinking has been, that the better quality of the wood is correlated to the slow growth.

The third phase can be called "development", where Australians and New Zealanders were ahead in research, but also South Africans and Chileans were implementing smaller scale studies. In Australia CSIRO (Commonwealth Scientific and Industrial Research Organization) and state government research groups shared the researching field. In New Zealand, the Forest Research Institute was mainly responsible for performing the radiata pine studies. (Mead 2013, 9.)

Especially in New Zealand a lot of effort was put into research regarding all the aspects, beginning from tree breeding and nursery to soils and entomology. These meticulous studies improved the practices in silviculture from not only to make the tree grow in general, but also to make the growth more efficient and profitable. Improved practices included among others introduction of fertilizers, and the development of a thinning and pruning schedule. At the time, the radiata pine started to become domesticated in Australia and New Zealand. (Mead 2013, 9-10.)

The fourth - now ongoing phase - began in the early 2000's. This is called "consolidation" (Mead 2013, 10). In this phase the aim is to ensure the sustainability of the plantations. Regarding the sustainability of forestry, there are four different aspects to be taken into consideration: ecological, social, economical, and cultural. This in order to guarantee balanced benefits of the forest for people, animals, and the nature for current and future generations. (Ministry of Agriculture and Forest of Finland.) A sustainable use of forests benefits both people and nature, locally and globally in the long term. On the contrary for example only short-term mass harvesting and financial goals can be very harmful in terms of climate change, biodiversity, and people's relationship, and understanding of nature.

4.2 Properties

The undisputed advantage of the radiata pine is its fast growth. In favourable soil and climate conditions, it grows in approximately 28-30 years to a mature state. Compared to Nordic trees, which take 65 to 120 years before the tree is ready to be felled (Metsägroup). In New Zealand, the fast growth of the radiata pine was noticed very early. It grew well on variable soil types such as gravels, clays, volcanic ash, and costal sand. Although it grew fast, it still had defects, for example fork trunks. Efficient and systematic breeding has helped to eliminate the unwanted properties, resulting in straight and almost knotless logs, trees which are stronger and resistant to some foliage diseases, and suitable for specific soil types and climate. (Berg, 2008.) Though Mead (2013, 77) sees that the less knotty stems are more the effect of the environment than genetics by writing that *Coarse-branched stems, however, are not found in slower-grown stands where moisture and fertility are limiting; environment is probably of greater importance than genetics.*

The radiata pine consists of 90-95% of tracheids. The length of tracheids is about 3-4mm in a mature tree but varies between the growing states and environment, heartwood, and sapwood, early- and latewood and, also between every tree. (Cown 1999, 12-13.) Tracheids purpose is to deliver water and they also have large impact to the mechanical properties of the wood (Puuproffa.)

In the Southern Hemisphere the cambium is active around the year, though with slower activity during winter months. This means that the growth of the tree does not stop. From the cross-section of the radiata pine earlywood can be recognised from its lighter colour and thin cell walls, whereas latewood sections are slightly darker in colour with thicker cell walls. (Mead 2013, 79.) Earlywood sections are wider and lower in density, whereas latewood sections are narrow and higher in density (Saranpää 1997,88). According to Cown (1999, 10) the difference between the start of the earlywood and the latest latewood can be from 250 kg/m^3 to 800 kg/m^3 in density which are the furthest points.

The radiata pine is a medium density softwood. Its basic dry weight density varies between 350-450 kg/m^3 depending on growing circumstances together with the growing state of the tree, sapwood and heartwood, earlywood, and latewood and internally the stem itself. (Cown 1999, 10.) In New Zealand, the radiata pine of highest density grows on the northern parts of the North Island. The radiata pine of lowest density grows on the South Island and in the central North Island on higher altitude lands and volcanic ash soils. (Berg 2008.)

The inner part of the log around the pith is called heartwood. It develops in a similar way in every pine tree species. The radiata pine begins to develop heartwood around the age of 12-14 years. The developing speed of heartwood is about half or slightly less of the annual ring growth. (Cown 1999, 7.) When the stem is felled, perhaps not straight away, but after some time heartwood can be seen as a darker part in the centre of the log. There are several reasons for the darkness. Heartwood is dead cell tissue, and it consists of extractives that prevent it to rot. Also resin content of the heartwood is high because sapwood produces resin and resin canals lead it towards the pith trough heartwood. Sapwood is highly water saturated and the moisture content can be 60%, as heartwood is much dryer with a moisture content of approximately 45%. Heartwood is low in permeability due to blocked pores. (Saranpää 1997, 86; Cown 1999, 10.)

The differences between sapwood and heartwood and, between earlywood and latewood which are mentioned in the previous paragraphs, have an impact to the wood processing. Heartwood is usually harder to treat because of its low permeability, high resin content and extractives. This also makes the use of heartwood slightly harder regarding chemical pulping. Instead, the sapwood of the radiata pine is relatively effortless to treat for example with protecting chemicals because of the good permeability and a low quantity of extractives. High content of resin both in heartwood and knots can cause problems in mechanical pulping. In the radiata pine the share of sapwood is larger than the one of heartwood. This together with its medium density and a rather low quantity of knots makes the machining easy. (Mead 2013, 80.)

4.3 The state of radiata pine in New Zealand

90 % of the global radiata pine plantations are located in three countries: New Zealand, Australia, and Chile. There are approximately 4.2 million hectares of radiata pine plantations in the world of which New Zealand and Chile have approximately 1.5 million hectares each. (Mead, 2013, 10,13.) 1.5 million hectares is close to 15% of all the forests in New Zealand. In total, forests cover 10.1 million hectares, of which approximately 80% of the forests in New Zealand are native. Some of the indigenous species have in major part been felled in the beginning of 1910's, which has led to a need for foreign species. Today most of the native forests are under conservation. (Ministry of Primary Industries, 2020.)

Forestry industry is one of the major industries in New Zealand with circa 6 billion NZD worth of exports. Radiata pine plantations have a remarkable role in the industry. It is the most planted species on the forest plantations in New Zealand as 90% of the plantations are radiata pine. The Douglas fir is the second most planted species with a share of only 6% of plantations. (Ministry of Primary Industries, 2020.)

The radiata pine has a wide range of end-use applications. It is used as traditional timber in buildings and furniture. It is also used in engineered timber products like CLT, LVL or plywood. Chips form the sawing process are used in wood-based panels production such as particleboard or MDF. Additionally, the radiata pine pulp is a source for the paper and packaging industry. The annual yield of the plantations is approximately 30 million cubic meters. Half of it is further processed and other half is exported as logs. New Zealand mainly exports timber to Japan, Korea, China, and India. (New Zealand Farm Forestry Association Inc, 2021.)

5 Thermal Modification

5.1 General

There have been various studies regarding the thermal modification of wood over the decades since the 1930's. The first studies have been performed in Germany and United States. During the 1990's these were accompanied by studies from France, Netherlands, and Finland. The most ample and specific studies have been performed by the VTT Technical Research Centre of Finland. (Thermo wood -handbook 2003, 1-1.)

It has been known since the times of the Vikings that burning the surface of wood will make it more durable in outdoor use. Under the thermal treatment chemical and physical properties of the wood changes. Heat has a similar effect to the structure of wood as ageing. VTT together with the Finnish wood industry have created an industrial scale thermal modification treatment. This is licensed for the members of the Thermo Wood Association. (Thermo wood -handbook 2003, 1-1.)

Thermal modification is an eco-friendly way to treat the wood. The process uses only heat, water, and water vapor. The thermal modification treatment has several benefits to the properties of wood, such as lighter weight of the wood, better biological durability, better dimensional stability in terms of swelling and shrinking, and better thermal insulation properties. Only disadvantage is that the process slightly weakens the bending strength of the wood. (Thermo wood -handbook 2003, 3-1.)

5.2 Process

Both softwood and hardwood can be thermally treated using the Thermo Wood method. Although every species needs an individual adjustment. Abodo's timber is thermally modified using the Thermo Wood process, which is adjusted to be suitable for the radiata pine (Tetri 2021). At the beginning of the thermal modification process the wood can be either green or kiln dried (Thermo wood -handbook 2003, 6-2).

In the first step of the process temperature is increased fast up to 100 °C and after that slowly lifted to 150 degrees Celsius until the wood is fully dried. The whole modification process can take approximately a day or two, in which the first step can last from 4 to 15 hours, depending on the species, the initial moisture content and the thickness of the wood. (Thermo wood -handbook 2003, 1-3.)

The second step in the process is the actual modifying part. The temperature is increased above 200 degrees Celsius if the process belongs to the Thermo-D class. In this the letter

D stands for durability. Another class is called Thermo-S, where the letter S stands for stability. In the Thermo-S process temperature is lifted only up to 190 Celsius degrees. Abodo's Radiata pine goes through the Thermo-D process. It is modified by rising the heat to 230 Celsius degrees, which is a slightly higher temperature than for Nordic trees. This step does not last longer than two to three hours. (Thermo wood -handbook 2003, 6-2 –1-3.)

The third step is to decrease the temperature back to the starting temperature. This process is approximately as long as the first step depending on wood species and t modifying temperature. The balancing is carefully controlled, and water steam is added to avoid cracking. Finally, the moisture content is increased to 5-7% to ensure it is good to machine. (Thermo wood -handbook 2003, 1-3.)

5.2.1 Chemical changes

This paragraph briefly explains the changes which occur in wood during the heating process without going deep into other chemical reactions. Depending on the species, the conifer tree consists about 45-50% cellulose, 25-30% hemicelluloses, 25-30% lignin, and 5% or less extractives. Cellulose and hemicelluloses are structural parts of the tree, whereas lignin has a supportive purpose in the cell walls giving the wood its stiffness. According to the Thermo Wood -handbook (2003, 2-4–3-4.) hemicelluloses degrade in lower temperatures than cellulose and lignin. As a result of chemical reactions, the number of hemicelluloses lowers in the wood. This can explain a better resistance to fungal decay as there is less nutrition for the fungi. The better dimension stability comes as a result of a decreased number of the water-absorbing hydroxyl groups, which is also connected to decomposition of the hemicelluloses. The typical brown colour for thermal modified wood comes from the chemical changes which take place in lignin above 120 Celsius degrees. Most of the extractives evaporate during the heating process.

5.2.2 Physical changes

Wood slightly loses density during the thermal modification process, which can be explained by the loss of mass during heating while dimensions are not changed, as density is calculated by dividing the mass with the volume of the piece. Density decreases as the temperature increases. Also, the bending strength reduces during the thermal treatment as it is strongly correlated to density. (Thermo wood -handbook 2021, 20.) Radiata pine is treated in 230 Celsius degrees and loses approximately 10% of the density due to higher treating temperature. According to Tetri (2021) treatment in a lower temperature than 230 Celsius degrees does not improve the properties of the wood in terms of the fungal decay resistance to the desired level.

Referring to the test results in the Thermo Wood -handbook (2021, 23) compression strength measured perpendicularly to the grain increases during the process. Also, compression strength measured parallel to the grain increases slightly. The positive impact occurs even if the wood is treated in higher temperatures like 220 Celsius degrees. Splitting strength lowers by 30% - 40% compared to unmodified wood, regardless of the treating time or temperature. The test results in the Thermo Wood -handbook are based on testing Nordic wood species and may not be exactly applied to the radiata pine as the modification temperature is higher and initial density of radiata pine is different.

6 Glued Laminated Timber

6.1 History

In 1901 a German carpenter Otto Karl Freidrich Hetzer patented his invention of straight glued laminated beam and several years later he did the same for his curved laminated timber construction. (Lehman 2018.) This innovation enabled the usage of timber in a totally new purpose. Gluing timber boards, lamellas, together increased the mechanical properties of wood, decreased the meaning of the defects of wood, and repealed dimensional limitations of the natural timber. Because of the very good stiffness and strength - weight ratio, glued timber beams were possible to use for example, in load-bearing applications replacing steel, and concrete. The breakthrough of the glued laminated timber, commonly known as glulam, took place in the Brussels International Exposition in 1910, in which the Reichseisenbahnhalle was built from glued laminated arches with 43m bearing span. Today glued laminated timber has large range of end-use applications. There are schools, sport halls, train stations, and bridges built of glulam, and glulam is also used in smaller items like furniture. (Liimapuu käsikirja 2014, 8,15.)

6.2 Manufacturing process

Glued laminated timber consists of lamellas which are glued together into a beam. After sawing a log, boards are dried to around 12-18% in moisture content. Dried boards are strength graded before finger jointing. Usually, glulam lamellas are finger jointed to get a desired length for the beam. Thicker lamellas from 33mm to 50mm are used for straight or just slightly curved beams and thinner ones from 12mm to 33mm are used for curved beams. Finger jointed boards are carefully planed ensuring the surface of the boards are smooth before applying the glue. The lamellas are set on the jigs for the pressing and pressed until adhesive is cured. Typically, glulam is cold pressed. Finally, the beam is planed again before labelling and packing. (Glulam Ltd 2021; Porteous & Kermani 2013, 18.)

Glued laminated timber can be glued either horizontally or vertically. In horizontal gluing the wider lengths of the cross sections are perpendicularly glued together and in vertical gluing the narrow lengths are glued together. (Porteous & Kermani 2013, 218.) Figure 1. demonstrates the cross sections of vertically glued timber and horizontally glued timber.

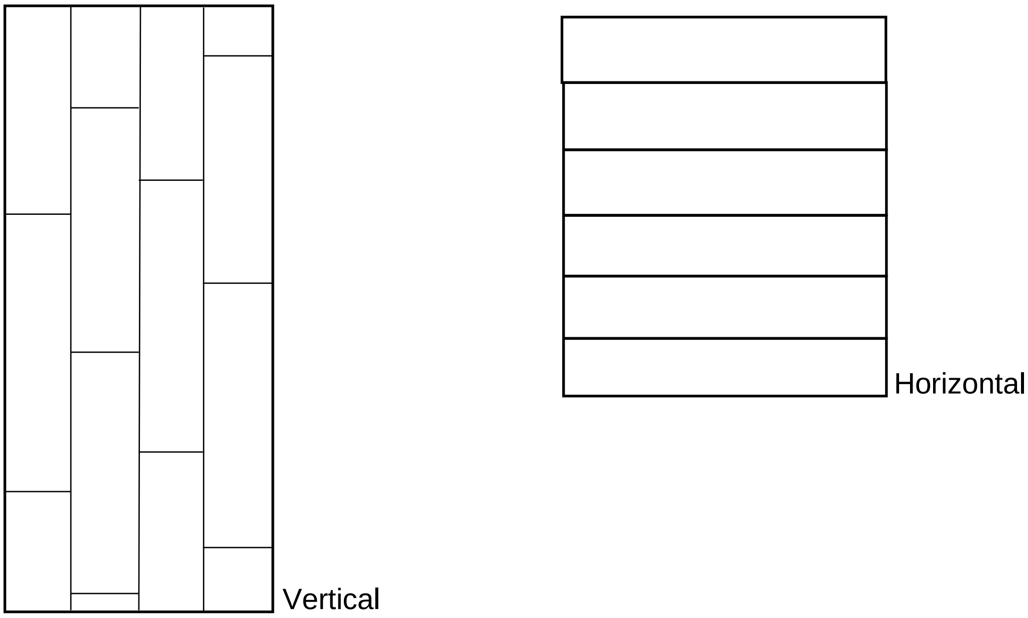

Figure 1. Cross sections of vertically glued laminated timber and horizontally glued laminated timber adapted from Porteous & Kermani (2013, 218)

Horizontal glulam is homogeneous if all the lamellas are from the same strength class and same species of softwood. Horizontal glulam can also be combined, when outer lamellas are from the higher strength class and middle ones from the lower strength class. Also, different species of softwood can be used in combined glulam. Glulam lamellas are divided to four strength classes by stiffness, strength, and density. The classes are GL 24, GL 28, GL 32, and GL 38. (Porteous & Kermani 2013, 220.)

6.3 Abodo’s vertical grain glulam

In this paragraph the glulam manufacturing process used by Abodo is introduced briefly. Logs are debarked in the forest before transported to sawmill. At the sawmill, the logs are first squared and then plainsawn. Side bits of the log are utilised in other use. Boards are kiln dried to 12-14% moisture content and afterwards thermally modified. In both steps there are left 5 centimetres extra to cover the shrinkage of the wood during the processes. (Campbell 2021a; Fischer 2021.)

From the sawmill the thermally modified timber is transported to a third-party company where the glue laminating is carried out. The boards are horizontally glued. In this stage the width of the board is 150mm (or 185mm for the wider profile). 1.5 cm is cut off both sides of the glued laminated block, ensuring the sides are straight. Then the block is turned 90 degrees and band sawn perpendicularly to grain into 20mm thick boards. The 20mm thick and

147mm wide boards are machine profiled. (Campbell 2021a; Fischer 2021.) In Figure 2. The Glulam manufacturing process is sketched roughly.

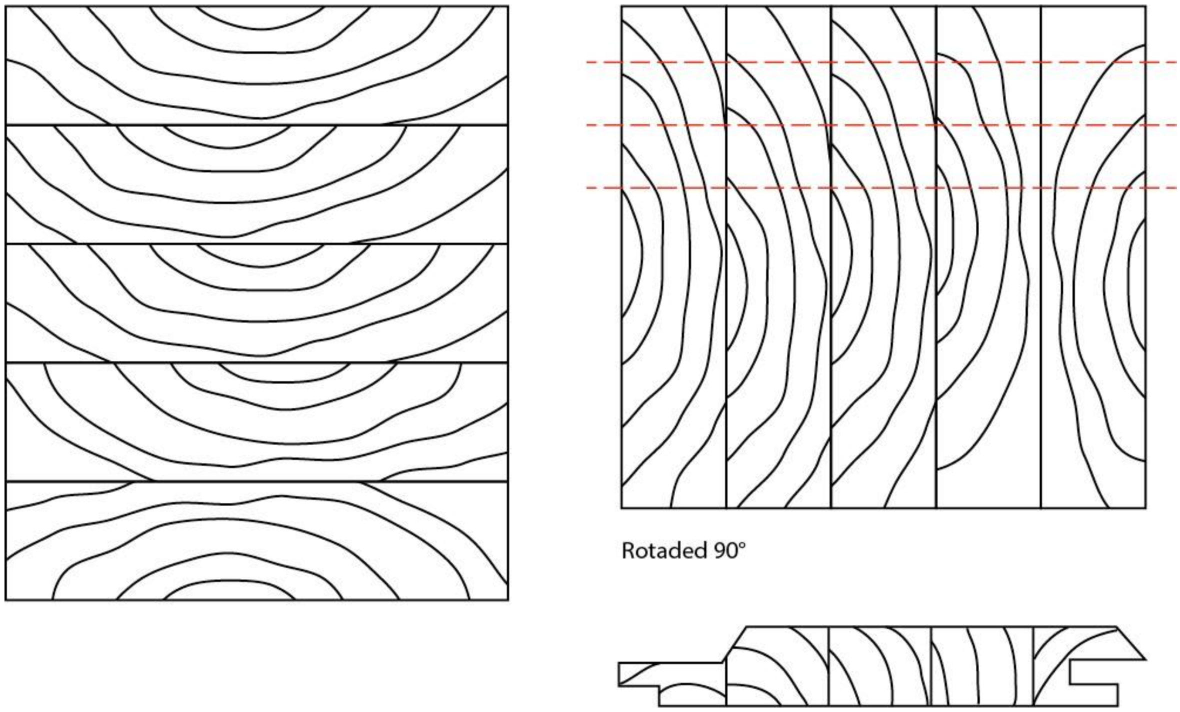

Figure 2. Glulam manufacturing process

7 Cross Laminated Timber

7.1 General

Cross laminated timber (CLT) has been invented in Germany and soon after the idea was copied and developed in Austria in early 90's. First CLT plants have been found in German speaking area in Europe in 1994-1995. CLT is an engineered massive timber product, which has better strength and dimension stability properties compared to traditional timber products or to glulam, on which the CLT is based. (Berger & Kers, 2021.)

CLT is used in family house developments, but it is fast becoming a significant competitor to concrete and steel as a high-rise building material. It can be used in load bearing walls, floors, and ceilings. Thickness of the panel may vary depending on the end-use application. CLT's significant advantage is its pre-fabrication, which leads to faster completion on a construction site. As a relatively light material compared to concrete, for lifting the panels heavy footings or big cranes are not required as for heavier materials. CLT has also good insulation properties and rather good fire resistance. (Karacabeyli & Gagnon 2019, 2.)

CLT consists of several layers of glued and finger-jointed board panels which are glued one upon the other in a 90 - degree angle. The number of the layers vary from three to nine. The configuration of the panels can be either so that every second panel is longitudinal, and the panel or panels in between are traverse or two panels on the top and bottom are longitudinal, and the rest of the panels in between are traverse. If the CLT panel is five layered and two of the top and bottom panels are longitudinal then there is only one traverse panel in the middle. Latter configuration is rarer and rather used in special applications. Top and bottom panels are always longitudinal. (Karacabeyli & Gagnon 2019, 6.)

7.2 Manufacturing process

The manufacturing process starts similarly as the Glulam process. Logs are sawn at the sawmill. Depending on the sawing pattern, the yield varies between 55-60%. Boards are dried to a 12-14% moisture content. Moisture content has an impact glue bonding. The sawing pattern has an impact for the shrinkage during the drying due to different directions of grains. A typical amount of shrinkage is 8% in tangential direction, 4% in radial direction and 0.1% in longitudinal direction. The percent may vary in different species. (Berger & Kers 2021.)

After drying the boards are visually and/or strength graded and planed from four sides. The size of the board components varies depending on manufacturer and desired size of the panel. Typically, the size of the boards, lamellas, are from 16mm to 51mm in thickness and from 60mm to 240mm in width. Because of the finger-jointing the length of the lamella boards is not limited. Lamellas can be glued together from the sides or left without the glue. (Karacabeyli & Gagnon 2019, 5.)

The glue is spread on the face side of the lamella boards and assembled for the lay-up. Typically, glue is spread by using a curtain coating method. The most common glue used in CLT is polyurethane (PUR). Sometimes also melamine urea formaldehyde (MUF) can be used. (Berger & Kers 2021.) Polyurethane is a thermoset glue and part of the chemically cured glue group. (Varis 2018.) Polyurethane cures in room temperature, therefore it does not require high temperature heat in pressing (Puuinfo 2020a). Its classification is D4 group by the EN 204 standard. It can be used for interior and exterior application (Kiilto Oy). Pressing is carried out with hydraulic, pneumatic, or vacuum press (Brandner 2013).

Typical dimensions of the CLT panels are 0.6m, 1.2m, 2.4m or 3m in width. 105mm, 175mm and, 245mm in thickness but also thicker panels are possible. In length CLT panels can be up to 18 meters. Dimensions vary depending on the manufacturer. Transportation may limit the size of the panels. (Karacabeyli & Gagnon 2019, 5.)

7.3 Mini-CLT panel

Mini-CLT is not very common product yet. Google search gave only a few results that responded to a thin CLT panels. The keywords of the search were “mini-clt panel”, “thin clt panel”, and “thermally modified clt panel”. According to Campbell (2021b) there are a couple thin CLT panel manufacturers in Europe who are using a lower grade thermally modified timber.

Abodo’s mini-CLT panel is made of thermally modified radiata pine lamellas. Lamellas are 6mm in thickness and 30-140mm in width. Lamellas are glued together from the sides before the glue is applied on the face side of the lamella board. The panel is formed of three layers. On the top of the board can also be glued a high-grade veneer. End-use application for the mini-CLT panel is primarily in exterior cladding use, but could be possibly used in interior walls, ceiling linings, and soffits. (Campbell 2021b.)

The purpose of the mini-CLT panel production is to maximise the usage of the timber because the lower grade timber can be utilised in CLT panels. That will also increase the production volumes. Prefabrication of the mini-CLT panels eases and speeds up the installation at the construction site. (Campbell 2021b.)

8 Property tests

8.1 Background

According to Accoya Wood information guide (2020, 10) untreated radiata pine shrinks from green to oven-dry approximately 7.9% in tangential direction and 3.8% in radial direction. Čermák, Rautakari, Horáček, Saake, Rademacher, and Sablík (2015) have studied dimensional stability of thermally modified wood. The experimented species were beech, poplar, and spruce. The specimens that were treated in 200 Celsius degrees improved the dimension stability approximately 36-54%.

The MOE of the radiata pine is approximately 9.1GPa. The result of the MOE is based on an experiment implemented by Grant, Anton, and Lind (1984, 4), where the impact of the knots to the strength of the wood was studied. Less knotty wood has better stiffness properties. Thermal modification decreases the strength properties of the wood due to mass loss.

8.2 Anti-swelling efficiency

The anti-swelling efficiency test for the thermally modified glulam, mini-CLT panel and solid timber were implemented at Abodo's facilities. Tests were adapted to the European standard EN317: Particleboards and fibreboards. Determination of swelling in thickness after immersion in water. In this project the swelling was measured in all dimensions. Particularly, the focus was on swelling in width wise.

There were 32 specimens of the glulam and mini-CLT, and 16 specimens of the solid TM tested. Mini-CLT specimens were cut from prototype panels, whereas glulam and solid TM are in commercial production. Each specimen was 50mm by 50mm +/- 2mm. The thicknesses of the specimens were 20mm +/-1mm in glulam, 18mm +/-1mm in mini-CLT, and 19mm +/-1mm in solid TM. In 0% moisture content average weight for glulam samples were 22 grams, mini-CLT 20 grams, and solid TM 21 grams.

Solid TM is measured by radial thickness, tangential width, and longitudinal length. Glulam and mini-CLT are measured by thickness, width, and length. Dimensions are marked in Figure 3.

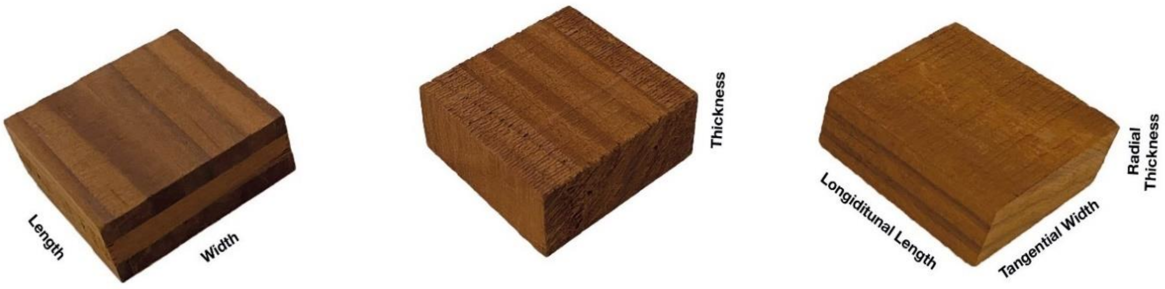

Figure 3. Mini-CLT, glulam, and solid TM specimens 50mmx50mm

8.2.1 Implementation

Preparations before the ASE test included cutting the specimens, measuring dimensions with a digital calliper, and weighted on scale with .00 accuracy. Every dimension was measured from the middle of the specimen, where calliper was set approximately in a 45 - degree angle. Initial moisture content was measured with the *Lingometer DuoTec C* moisture meter. After each specimen was measured, they were oven dried for 24 hours in 103 +/-2 Celsius degrees to drop moisture content to 0%. In Figure 4. solid TM specimens after taken out from the oven. All the dimensions were measured and weighted again after oven drying.

Figure 4. Solid TM specimens after the first oven dry

Immersion was carried out in a plastic container. The size of the container was 480mm x 35mm x 25mm. The container was filled up with water. On the top of the specimens were set a net to ensure the specimens stay immersed at least 2.5cm below the water surface but not touching the bottom of the container. Water temperature was 20 +/-2 Celsius degrees. PH value of the water was approximately 7.5.

Specimens were measured and weighted after 24 hours, 48 hours, 7 days, and 14 days immersion. Water was changed in every measuring point. ASE was calculated using the following formula:

$$G = \frac{t_2 - t_1}{t_1} * 100 \quad (1)$$

Where t_2 is the dimension after immersion, t_1 is an oven-dry dimension and G is the difference of the change in percent. Last step was to oven dry and measure the specimens one more time. Moisture content of the specimens were calculated after each measuring point using the following formula:

$$H = \frac{m_2 - m_1}{m_1} * 100 \quad (2)$$

In the formula H stands for moisture content %, m_2 is a mass after immersion and m_1 is a mass after oven drying when moisture content is 0%.

8.2.2 Results

All specimens in glulam, mini-CLT, and solid TM were fully saturated (MC over 30%) after 24 hours immersion when average moisture content was approximately 50%. Average of the highest moisture content % reached over 100% on glulam and solid TM. The moisture content of the mini-CLT was just slightly below 100% on its highest. Figure 5. presents the changes in moisture content. After second oven-dry all the specimens were lighter than after the first oven-dry. Initial moisture content calculated with oven-dry method was 5.6% for glulam, 6.0% for mini-CLT, and 6.1% for solid TM.

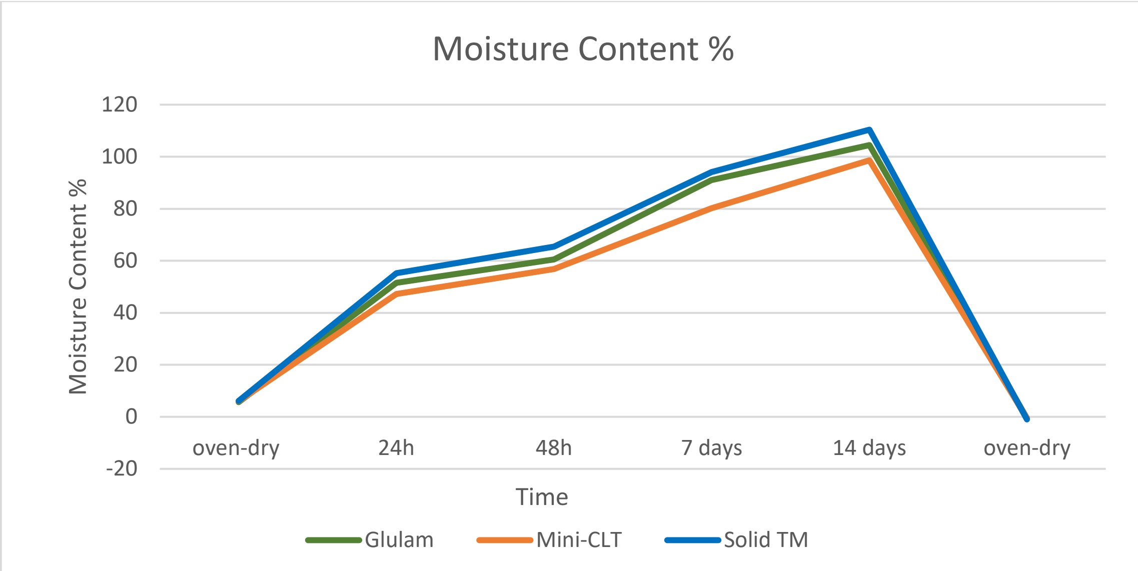

Figure 5. Changes in moisture content

The density of the solid TM specimens was averagely 439kg/m^3 in 0% moisture content, which is relatively high density to New Zealand radiata pine considering the wood has already lost approximately 10% of the density due to thermal modification. Density was calculated with the formula below:

$$D = \frac{m_d}{R_d * T_d * L_d} kg/m^3 \qquad (3)$$

In the formula D is density, m_d is weight after oven-dry, R_d is radial thickness after oven-dry, T_d is tangential width after oven-dry, and L_d is longitudinal length after oven-dry.

Changes in thickness were similar in glulam and mini-CLT. The anti-swelling efficiency of the glulam was 4.4% +/- 0.1%, mini-CLT 5.4% +/- 0.2%, and solid TM 2.7% +/- 0.2% on 95% confidence level. Figure 6. shows the differences between the swelling percent in different groups. In the figure the first oven-dry is marked 0%. Original dimension and dimensions after the immersion are compared to the first oven-dry dimension.

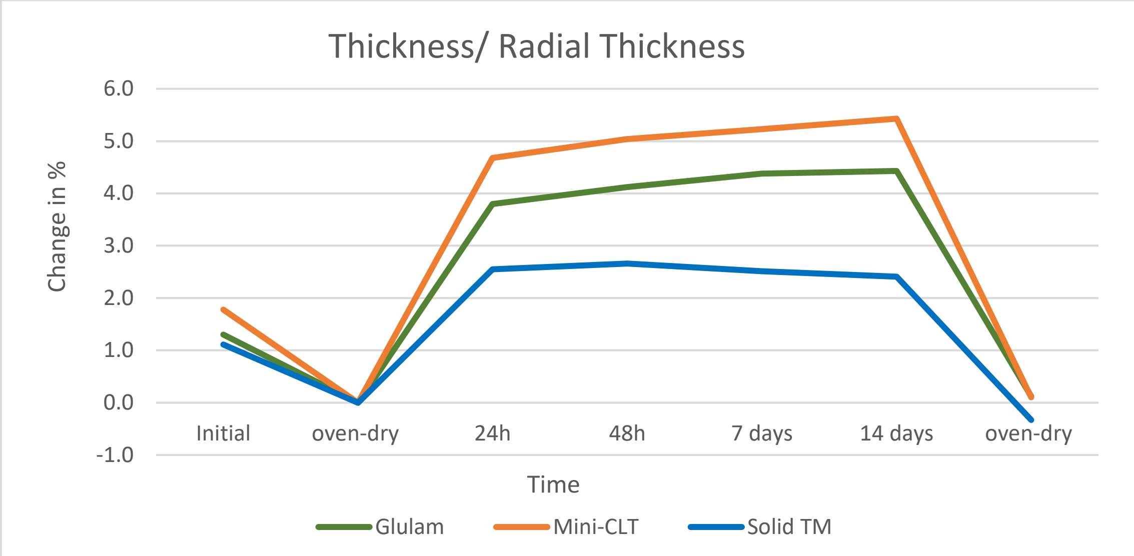

Figure 6. Changes in thickness/radial thickness during the immersion

Changes in width wise were the most remarkable. As figure 7. shows, the mini-CLT swells remarkably less than solid TM or glulam during the 24h immersion. Mini-CLT panel swelled 0.8% +/- 0.1% on 95% confidence interval, when glulam swelled 1.9% +/-0.2% and solid TM swelled 4.0% +/- 0.2%. The further swelling was minimal, less than 0.4%, in all groups when the immersion continued after the first day of immersion.

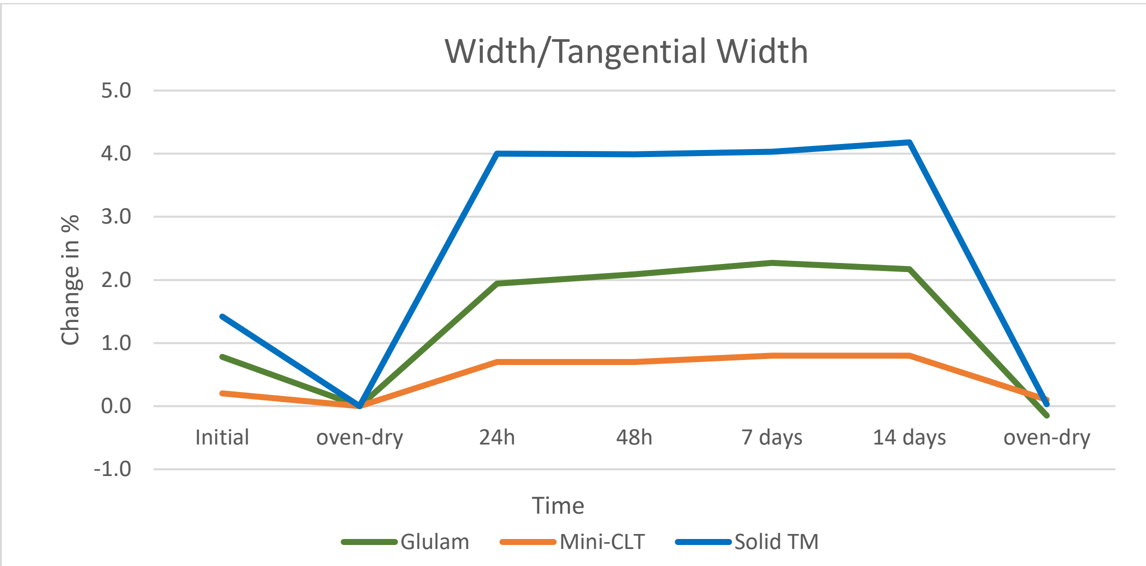

Figure 7. Change in width/tangential width

In length wise swelling was the most even between the groups. Glulam swelled 0.45% +/- 0.2%. on its highest after the 24 hours immersion, mini-CLT swelled 0.4% +/-0.1% on its highest and stayed on the same level until the second oven dry. In second oven-dry mini-CLT shrank 0.1% compared to the oven-dry length. Instead, glulam did not recover to the same length after the second oven-dry leaving 0.13% from the first oven-dry length. The figure 8. shows similarities between the swelling of the glulam and solid TM. Although the glulam swelled more the patterns of the lines are very similar.

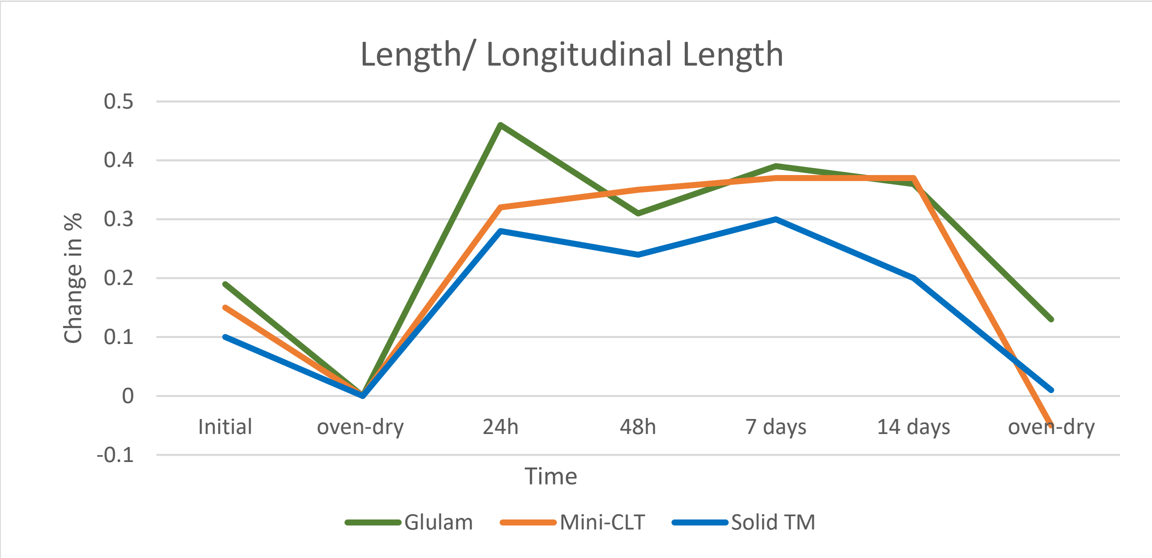

Figure 8. Changes in length/longitudinal length

If the mini-CLT and solid TM are compared to the Accoya Wood and the Kebony Wood in the movement from green to oven-dry, the movement of the Accoya Wood is the smallest in radial direction. In tangential direction the smallest movement occurred with the mini-CLT, 0.7%. The structure of the CLT blocked the movement of the mini-CLT panel in width wise. Instead, the movement of the mini-CLT is the highest in thickness wise. Results are shown in table 1.

Treatment	**Tangential movement %**	**Radial movement %**
Accoya Wood	1.6%	0.8%
Kebony Wood	2.5%	1.4%
Mini-CLT panel	0.7% (width)	4.5% (thickness)
Solid TM	3.8%	2.5%

Table 1. The comparison of the movements. The results of the Accoya Wood and Kebony Wood are from the Accoya Wood information guide (2020, 10)

8.3 Modulus of Elasticity and Modulus of Rupture

8.3.1 General

Several properties of the wood have an impact to the strength of wood. For example, the quality, number, and location of the knots, twisting, and cracking are the factors that effect to the strength. Timber can be strength graded visually. The person who is in charge of the grading must have passed timber strength grading course. Machine vision, x-ray, or ultra-sound are used in machine grading. Machine grading is more accurate as it is based on algorithms when visually grading is based on human's decisions. (Puuinfo 2020b.) Although the machine grading is already significantly more accurate, compared to visual grading by human, development has not stopped. Technology industry together with forestry industry develop new machines and software to maximise the yields. For example, a Finnish company called Microtec Oy has developed a new grading system based on AI. According to Koponen (2021) the grading simulations, where AI was used together with algorithms gave better results compared to the grading tests which were based on algorithms without AI.

8.3.2 Implementation

The tests were implemented in the Materials and Testing Laboratories Ltd in Auckland. The tests were based on the European EN310 standard: Wood-based panels. Determination of modulus of elasticity in bending and of bending strength. All the specimens were balanced to a 65% relative humidity before testing. The specimens were set face wise on the top of the supports leaving 250mm on the outer sides of the supports. The load was added in the middle of the centres of the supports. The test setup is shown in figure 9. MOE describes resistance to deflection and MOR describes the point of the failure. 30 specimens of glulam and 15 pieces of mini-CLT panel were tested. Mini-CLT panel specimens were 300mm x 50mm and glulam specimens were 410mm x 50mm. Thickness of the specimens were the same as in the ASE tests (glulam 20mm, mini-CLT 18mm, solid TM 19mm). The test was implemented longitudinally face wise. This test did not include testing in longitudinally traverse wise. MOE was calculated with the formula (3) and MOR with the formula (4).

Figure 9. Glulam specimen in MOE/MOR test (Lee, 2021a)

$$E_m = \frac{{l_1}^3(F_2 - F_1)}{4bt^3(a_2 - a_1)} \quad (4)$$

$$F_m = \frac{3F_{max}l_1}{2bt^2} \quad (5)$$

- E_m = MOE
- F_m = MOR
- l_1 = Distance between the centres of the supports
- b = Width of the pieces in mm
- t = Thickness of the pieces in mm
- F_2 - F_1 = Is the increment of the load (in N) on the straight-line portion of the load-deflection curve. F_1 is circa 10% and F_2 circa 40% of the maximum load
- $a_2 – a_1$ = Is the increment of the deflection at the mid-length of the test piece

8.3.3 Results

In MOE and MOR tests the mini-CLT, and glulam are not necessarily comparable, because of the different structure of the pieces. The mini-CLT specimens were shorter, and glulam specimens were taken from the commercially manufactured batch, whereas mini-CLT specimens were taken from 3 panels that were prototypes, also the sampling sizes varied. Regardless, results can be directional. The results of the MOE and MOR are presented in table 2.

	Glulam	Standard Deviation	Mini-CLT	Standard Deviation
Weight (g)	166,4	-	127	-
Max Load (N)	1638	303	389	77
Deflection (mm)	7.0	1.1	3.9	0.8
Modulus of Rupture (MPa)	52.77	9.72	9.31	1.72
Modulus of Elasticity (GPa)	8.75	1.03	1.72	0.30

Table 2. Results of the MOE and MOR

There was a significant difference in results between glulam and mini-CLT. The mini-CLT specimens were cut across from the panel. Due to that the wood was bended mainly perpendicular to grain as can been seen in figure 10. The grain direction of the middle lamella board was parallel to the length of the specimen and in practice the test was measuring the bending strength of this middle lamella board. The strength of the wood in perpendicular to grain direction is weak and failure occurs easily. The glulam specimens were tested parallel to grain.

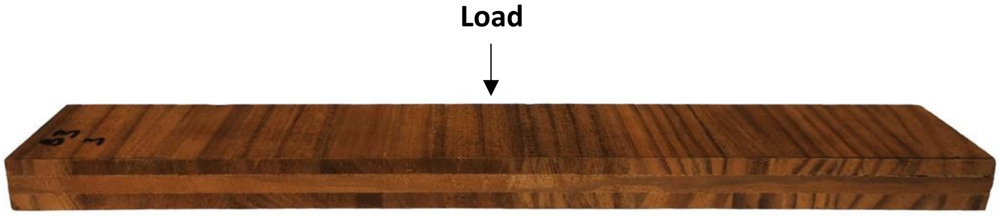

Figure 10. Mini-CLT specimen for MOE/MOR test

All the mini-CLT specimens failed from the bottom in consequence of tension at the bottom surface. The failures appeared specifically on lamellas, whereas glue lines were intact. In the figure 11. are shown the failure in glulam and in mini-CLT specimens. In the mini-CLT specimens it was hard to visibly see the failures, whereas in glulam specimens the failure was clearer. The failure in mini-CLT is hard to see because of the strength of the middle layer is still holding the panel straight. In figure 12 there is a close look of the broken off mini-CLT.

Figure 11. The failure after MOE/MOR test in mini-CLT and glulam (Lee, 2021b)

Figure 12. Mini-CLT after failure in bending

8.4 Weathering

The weathering test process for the mini-CLT panels have started approximately a month ago. Two boards, 1200mm wide and 1190mm high, were installed on the weathering racks in 45 - degrees angle facing north. See in figure 13. Between the two panels has been left 4mm gap, which can be seen in figure 14. Top of the panels were coated with Abodo’s end shield. Exact four millimetres cap helps to observe the swelling in width wise during the weathering process. In addition of swelling/shrinkage, also cracking will be observed.

Figure 13. Mini-CLT panels weathering

Figure 14. Mini-CLT panels photographed from the top. The top of the panels is coated with end shield.

After the four weeks of weathering no cracking has occurred on the panels. The gap between the panels has slightly narrowed, as the weather has been rainy in past weeks. The weathering process will be carried on after the thesis project.

9 Conclusion

The purpose of the thesis was to study anti-swelling efficiency and strength properties of thermally modified mini-CLT panel aimed for exterior use, such as cladding. The result of the anti-swelling test in width was slightly higher than expected (0.5%). Mini-CLT swelled 0.8% +/-0.2% in width during the 14 days immersion, when the result was compared to the oven-dry width. Compared to the initial width (5.7% MC), the swelling was 0.6% +/-0.1% on 95% confidence interval. The results are primarily compared to the first oven-dry dimension. When the swelling is calculated from the oven-dry dimension, it ensures that all the specimen groups were in same condition at the starting point. Regardless, the final result for mini-CLT was very close to the expectation and also lower than in other specimen groups glulam and solid TM. The result was better for mini-CLT because of the CLT structure has a positive impact in dimension stability in width wise, whereas glulam swelled 2.3% +/-0.2% in width and solid TM swelled 4.2% +/-0.2% in tangential width. Instead, in thickness wise the mini-CLT swelled the most, almost 3 %-unit more compared to the solid TM. Wood is hygroscopic and it naturally swells and shrinks depending on the relative humidity of the air, and when the natural swelling direction is blocked by the CLT structure, it may push the swelling other direction. In exterior cladding use the swelling of the thickness does not necessarily have significant meaning as long as the swelling in width and in length wise are minimal. The swelling of the mini-CLT was 0.4% +/-0.1% in length wise.

The swelling of the thickness may have more impact in interior use, but it is very unlikely that the mini-CLT would expose to such wetting as in ASE test. Regardless, that would be interesting to study more especially if there will be other than exterior end-use application for the mini-CLT panel.

ASE test results also showed that the sample mass lowered (approximately -0.5-1.0%) in every group after the second oven-dry compared to the first oven-dry which indicates that something of the wood has dissolved into the water. Glue lines did not show any splitting in glulam or mini-CLT.

In MOE/MOR test the mini-CLT showed clearly weaker result compared to the glulam. The bending strength of the mini-CLT was 9.31MPa +/-0.87MPa and the glulam 52.35MPa +/-3.48MPa on 95% confidence level. Glulam was tested parallel to the grain whereas in mini-CLT specimens the grain directions of the top and bottom layer lamellas were perpendicular to grain. The grain direction of the wood has a substantial meaning to the MOE. The MOE of the wood can be even hundred times better in parallel to grain compared to perpendicularly to grain (Puuinfo 2020c). The average deflection of the glulam was 7.0mm with 1.1mm standard deviation and the deflection of the mini-CLT was 3.9mm with 0.8mm standard deviation. The wood is stiffer and more flexible parallel to the grain direction. Due to that the deflection of the glulam was higher than mini-CLT. The mini-CLT requires more studies in terms of the strength properties. It could be expected that the results regarding the mini-CLT would be better in MOE/MOR, if the specimens were cut vertically from the panel, so that the grain direction of the top and bottom lamellas would be parallel to grain in test specimens. Also, different lay-up of the panel can possibly improve the strength properties. For example, the top and middle lamella boards can be orientated to the same grain direction and the bottom lamella board orientated in 90° angle towards the middle lamella board.

The tests gave good directional results about the behaviour of the mini-CLT. Panel itself is an interesting product in terms of several end-use application options (exterior and interior). The panel is easy to machine to desired shape, which can also add the end-use options. Although coating probably requires a new coating line. Possibility to utilise lower grade timber, reduce the waste and maximise the yield are factors that benefit the company and also nature.

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Appendix 1.

Mini-CLT results in width

									Compared to the first oven-dry							Compared to the initial			
Sample #	Initial	Oven-dry	24h	48h	7 days	14 days	2nd oven dry		initial	24h	48h	7d	14d	2nd oven-dry		24h	48h	7d	14d
1	49.88	49.82	50.10	50.10	50.04	50.17	49.87		0.12	0.56	0.56	0.44	0.70	0.10		0.4	0.44	0.32	0.58
2	50.00	49.90	50.29	50.33	50.50	50.46	49.99		0.20	0.78	0.86	1.20	1.12	0.18		0.9	0.66	1.00	0.92
3	49.78	49.69	50.08	50.13	50.19	50.13	50.48		0.18	0.78	0.89	1.01	0.89	1.59		0.7	0.70	0.82	0.70
4	49.93	49.88	50.20	50.29	50.30	50.34	49.95		0.10	0.64	0.82	0.84	0.92	0.14		0.8	0.72	0.74	0.82
5	49.53	49.42	49.87	49.91	49.86	49.88	49.46		0.22	0.91	0.99	0.89	0.93	0.08		0.7	0.77	0.67	0.71
6	49.62	49.52	49.85	49.8	49.96	49.89	49.60		0.20	0.67	0.57	0.89	0.75	0.16		0.5	0.36	0.69	0.54
7	49.41	49.34	49.72	49.78	49.79	49.81	49.38		0.14	0.77	0.89	0.91	0.95	0.08		0.8	0.75	0.77	0.81
8	49.66	49.58	49.94	49.91	49.97	49.91	49.63		0.16	0.73	0.67	0.79	0.67	0.10		0.5	0.50	0.62	0.50
9	50.01	49.91	50.33	50.23	50.24	50.28	49.95		0.20	0.84	0.64	0.66	0.74	0.08		0.5	0.44	0.46	0.54
10	50.15	50.06	50.41	50.53	50.59	50.58	50.07		0.18	0.70	0.94	1.06	1.04	0.02		0.9	0.76	0.88	0.86
11	49.93	49.58	49.90	49.94	49.95	50.00	49.58		0.71	0.65	0.73	0.75	0.85	0.00		0.1	0.02	0.04	0.14
12	49.65	49.54	49.95	49.91	49.99	50.08	49.57		0.22	0.83	0.75	0.91	1.09	0.06		0.9	0.52	0.68	0.87
13	49.69	49.57	49.84	49.88	49.89	49.87	49.59		0.24	0.54	0.63	0.65	0.61	0.04		0.4	0.38	0.40	0.36
14	49.92	49.82	50.27	50.31	50.32	50.51	49.87		0.20	0.90	0.98	1.00	1.38	0.10		1.2	0.78	0.80	1.18
15	49.94	49.91	50.27	50.30	50.33	50.35	49.84		0.06	0.72	0.78	0.84	0.88	-0.14		0.8	0.72	0.78	0.82
16	49.86	49.70	50.36	50.16	50.20	50.27	49.77		0.32	1.33	0.93	1.01	1.15	0.14		0.8	0.60	0.68	0.82
17	49.89	49.70	50.08	50.20	50.11	50.06	49.81		0.38	0.76	1.01	0.82	0.72	0.22		0.3	0.62	0.44	0.34
18	49.87	49.86	50.05	50.05	50.37	50.08	49.92		0.02	0.38	0.38	1.02	0.44	0.12		0.4	0.36	1.00	0.42
19	50.28	50.25	50.41	50.47	50.56	50.59	50.28		0.06	0.32	0.44	0.62	0.68	0.06		0.6	0.38	0.56	0.62
20	50.25	50.01	50.34	50.40	50.44	50.40	50.13		0.48	0.66	0.78	0.86	0.78	0.24		0.3	0.30	0.38	0.30
21	50.26	49.86	50.48	50.12	50.42	50.54	50.10		0.80	1.24	0.52	1.12	1.36	0.48		0.6	-0.28	0.32	0.56
22	49.82	49.76	50.16	50.18	50.27	50.33	49.74		0.12	0.80	0.84	1.02	1.15	-0.04		1.0	0.72	0.90	1.02
23	49.51	49.24	49.66	49.76	49.88	49.77	49.21		0.55	0.85	1.06	1.30	1.08	-0.06		0.5	0.50	0.75	0.53
24	49.87	49.66	50.04	49.99	49.96	49.94	50.99		0.42	0.77	0.66	0.60	0.56	2.68		0.1	0.24	0.18	0.14
25	49.81	49.60	49.99	49.98	49.99	49.97	49.60		0.42	0.79	0.77	0.79	0.75	0.00		0.3	0.34	0.36	0.32
26	49.11	49.10	49.14	49.21	49.29	49.21	48.96		0.02	0.08	0.22	0.39	0.22	-0.29		0.2	0.20	0.37	0.20
27	50.26	50.23	50.35	50.33	50.36	50.42	50.10		0.06	0.24	0.20	0.26	0.38	-0.26		0.3	0.14	0.20	0.32
28	50.08	49.90	50.35	50.35	50.54	50.42	50.02		0.36	0.90	0.90	1.28	1.04	0.24		0.7	0.54	0.92	0.68
29	49.81	49.69	50.22	50.19	50.22	50.25	49.77		0.24	1.07	1.01	1.07	1.13	0.16		0.9	0.76	0.82	0.88
30	50.69	50.60	50.77	50.79	50.75	50.81	49.85		0.18	0.34	0.38	0.30	0.42	-1.48		0.2	0.20	0.12	0.24
31	49.82	49.85	49.99	49.96	49.99	50.13	49.80		-0.06	0.28	0.22	0.28	0.56	-0.10		0.6	0.28	0.34	0.62
32	50.12	50.11	50.51	50.55	50.56	50.58	50.07		0.02	0.80	0.88	0.90	0.94	-0.08		0.9	0.86	0.88	0.92
								Min	-0.06	0.08	0.20	0.26	0.22	-1.48		0.14	-0.28	0.04	0.14
								Maks	0.80	1.33	1.06	1.30	1.38	2.68		1.18	0.86	1.00	1.18
Total Ave	**49.89**	**49.77**	**50.12**	**50.13**	**50.18**	**50.19**	**49.84**	Ave	**0.2**	**0.7**	**0.7**	**0.8**	**0.8**	**0.1**		**0.60**	**0.48**	**0.59**	**0.61**
								Stand dev	0.19	0.26	0.24	0.27	0.27	0.60		0.27	0.25	0.26	0.26
								Conf 95%	0.07	0.09	0.08	0.09	0.09	0.21		0.09	0.09	0.09	0.09
								Conf 99%	0.09	0.12	0.11	0.12	0.12	0.27		0.12	0.12	0.12	0.12
								Max/min	0.43	0.62	0.43	0.52	0.58	2.08		0.52	0.57	0.48	0.52

Appendix 2.

Glulam results in thickness

	Thikness comparison								Compared to the first oven-dry							Compared to the initial			
Sample #	Initial	Oven-dry	24h	48h	7 days	14 days	2nd oven-dry		Shrinkage	24h	48h	7days	14days	2nd oven-dry		24h	48h	7d	14d
1	19.88	19.61	20.29	20.41	20.46	20.43	19.62		1.38	3.47	4.08	4.33	4.18	0.05		2.06	2.67	2.92	2.77
2	19.86	19.68	20.37	20.60	20.43	20.31	19.61		0.91	3.51	4.67	3.81	3.20	-0.36		2.57	3.73	2.87	2.27
3	19.79	19.68	20.37	20.49	20.48	20.60	19.59		0.56	3.51	4.12	4.07	4.67	-0.46		2.93	3.54	3.49	4.09
4	19.94	19.68	20.51	20.44	20.41	20.46	19.66		1.32	4.22	3.86	3.71	3.96	-0.10		2.86	2.51	2.36	2.61
5	19.88	19.59	20.40	20.43	20.47	20.54	19.56		1.48	4.13	4.29	4.49	4.85	-0.15		2.62	2.77	2.97	3.32
6	19.83	19.51	20.31	20.36	20.39	20.45	19.63		1.64	4.10	4.36	4.51	4.82	0.62		2.42	2.67	2.82	3.13
7	19.76	19.48	20.44	20.33	20.39	20.5	19.53		1.44	4.93	4.36	4.67	5.24	0.26		3.44	2.88	3.19	3.74
8	19.87	19.54	20.34	20.48	20.39	20.53	19.67		1.69	4.09	4.81	4.35	5.07	0.67		2.37	3.07	2.62	3.32
9	19.63	19.48	20.13	20.26	20.35	20.31	19.41		0.77	3.34	4.00	4.47	4.26	-0.36		2.55	3.21	3.67	3.46
10	20.04	19.81	20.50	20.59	20.80	20.83	19.81		1.16	3.48	3.94	5.00	5.15	0.00		2.30	2.74	3.79	3.94
11	19.99	19.79	20.53	20.60	20.64	20.84	19.79		1.01	3.74	4.09	4.30	5.31	0.00		2.70	3.05	3.25	4.25
12	20.04	19.79	20.59	20.64	20.67	20.72	19.81		1.26	4.04	4.30	4.45	4.70	0.10		2.74	2.99	3.14	3.39
13	20.04	19.82	20.59	20.54	20.64	20.63	19.80		1.11	3.88	3.63	4.14	4.09	-0.10		2.74	2.50	2.99	2.94
14	20.06	19.87	20.60	20.63	20.67	20.69	19.89		0.96	3.67	3.82	4.03	4.13	0.10		2.69	2.84	3.04	3.14
15	20.01	19.81	20.47	20.62	20.81	20.82	19.83		1.01	3.33	4.09	5.05	5.10	0.10		2.30	3.05	4.00	4.05
16	20.06	19.88	20.57	20.62	20.79	20.79	19.87		0.91	3.47	3.72	4.58	4.58	-0.05		2.54	2.79	3.64	3.64
17	20.05	19.82	20.51	20.57	20.61	20.57	19.80		1.16	3.48	3.78	3.99	3.78	-0.10		2.29	2.59	2.79	2.59
18	20.15	19.72	20.54	20.76	20.59	20.63	19.77		2.18	4.16	5.27	4.41	4.61	0.25		1.94	3.03	2.18	2.38
19	19.94	19.69	20.46	20.50	20.51	20.50	19.64		1.27	3.91	4.11	4.16	4.11	-0.25		2.61	2.81	2.86	2.81
20	19.97	19.78	20.78	20.59	20.63	20.64	19.75		0.96	5.06	4.10	4.30	4.35	-0.15		4.06	3.10	3.30	3.36
21	20.02	19.79	20.52	20.52	20.54	20.59	19.79		1.16	3.69	3.69	3.79	4.04	0.00		2.50	2.50	2.60	2.85
22	19.99	19.68	20.45	20.52	20.58	20.48	19.73		1.58	3.91	4.27	4.57	4.07	0.25		2.30	2.65	2.95	2.45
23	20.07	19.72	20.45	20.48	20.72	20.54	19.75		1.77	3.70	3.85	5.07	4.16	0.15		1.89	2.04	3.24	2.34
24	19.96	19.69	20.51	20.65	20.57	20.60	19.78		1.37	4.16	4.88	4.47	4.62	0.46		2.76	3.46	3.06	3.21
25	20.08	19.73	20.43	20.61	20.68	20.63	19.77		1.77	3.55	4.46	4.82	4.56	0.20		1.74	2.64	2.99	2.74
26	20.06	19.66	20.51	20.57	20.58	20.62	19.69		2.03	4.32	4.63	4.68	4.88	0.15		2.24	2.54	2.59	2.79
27	20.20	19.85	20.43	20.65	20.70	20.66	19.97		1.76	2.92	4.03	4.28	4.08	0.60		1.14	2.23	2.48	2.28
28	20.09	19.85	20.51	20.56	20.68	20.70	19.91		1.21	3.32	3.58	4.18	4.28	0.30		2.09	2.34	2.94	3.04
29	20.15	19.82	20.55	20.60	20.78	20.68	19.91		1.66	3.68	3.94	4.84	4.34	0.45		1.99	2.23	3.13	2.63
30	20.24	19.84	20.50	20.55	20.70	20.69	19.90		2.02	3.33	3.58	4.33	4.28	0.30		1.28	1.53	2.27	2.22
31	20.08	19.82	20.77	20.61	20.73	20.69	20.07		1.31	4.79	3.99	4.59	4.39	1.26		3.44	2.64	3.24	3.04
32	20.27	19.93	20.59	20.57	20.68	20.67	19.89		1.71	3.31	3.21	3.76	3.71	-0.20		1.58	1.48	2.02	1.97
								Min	0.56	2.92	3.21	3.71	3.20	-0.46		1.14	1.48	2.02	1.97
								Max	2.18	5.06	5.27	5.07	5.31	1.26		4.06	3.73	4.00	4.25
Total Ave	**20.00**	**19.73**	**20.48**	**20.54**	**20.59**	**20.60**	**19.75**		**1.4**	**3.8**	**4.12**	**4.38**	**4.43**	**0.12**		**2.4**	**2.7**	**3.0**	**3.0**
								Stand. Dev	0.38	0.47	0.41	0.35	0.46	0.34		0.57	0.47	0.44	0.58
								C 95%	0.13	0.16	0.14	0.12	0.16	0.12		0.20	0.16	0.15	0.20
								C 99%	0.17	0.22	0.19	0.16	0.21	0.15		0.26	0.21	0.20	0.26
								Max/min	0.81	1.07	1.03	0.68	1.05	0.86		1.46	1.12	0.99	1.14

Appendix 3.

Solid TM results in longitudinal length

Longitudinal length									Compared to the first ove-dry							Compared to the initial			
Sample	Initial	Oven dry	24h	48h	7 days	14 days	2nd oven dry		initial	24h	48h	7d	14d	2nd oven-dry		24h	48h	7d	14d
1	50.35	50.30	50.39	50.46	50.35	50.36	50.32		0.10	0.18	0.32	0.10	0.12	0.04		0.08	0.22	0.00	0.02
2	50.24	50.22	50.26	50.39	50.32	50.27	50.19		0.04	0.08	0.34	0.20	0.10	-0.06		0.04	0.30	0.16	0.06
3	50.15	50.01	50.10	50.12	50.11	50.06	50.06		0.28	0.18	0.22	0.20	0.10	0.10		-0.10	-0.06	-0.08	-0.18
4	50.10	50.03	50.10	50.19	50.10	50.10	50.05		0.14	0.14	0.32	0.14	0.14	0.04		0.00	0.18	0.00	0.00
5	50.33	50.24	50.31	50.32	50.59	50.31	50.25		0.18	0.14	0.16	0.70	0.14	0.02		-0.04	-0.02	0.52	-0.04
6	50.30	50.31	50.62	50.65	50.34	50.33	50.28		-0.02	0.62	0.68	0.06	0.04	-0.06		0.64	0.70	0.08	0.06
7	50.66	50.58	50.71	50.70	51.48	50.64	50.58		0.16	0.26	0.24	1.78	0.12	0.00		0.10	0.08	1.62	-0.04
8	50.61	50.58	50.68	50.66	50.64	50.63	50.59		0.06	0.20	0.16	0.12	0.10	0.02		0.14	0.10	0.06	0.04
9	50.30	50.26	50.38	50.43	50.41	50.35	50.32		0.08	0.24	0.34	0.30	0.18	0.12		0.16	0.26	0.22	0.10
10	52.32	52.36	52.40	52.42	52.37	52.38	52.23		-0.08	0.08	0.11	0.02	0.04	-0.25		0.15	0.19	0.10	0.11
11	51.02	50.96	51.25	51.08	51.06	51.02	50.99		0.12	0.57	0.24	0.20	0.12	0.06		0.45	0.12	0.08	0.00
12	51.05	51.01	51.15	51.06	51.1	51.06	51.01		0.08	0.27	0.10	0.18	0.10	0.00		0.20	0.02	0.10	0.02
13	50.61	50.52	50.69	50.67	50.62	50.66	50.55		0.18	0.34	0.30	0.20	0.28	0.06		0.16	0.12	0.02	0.10
14	50.67	50.62	50.96	50.68	50.74	50.91	50.60		0.10	0.67	0.12	0.24	0.57	-0.04		0.57	0.02	0.14	0.47
15	50.92	50.89	50.96	50.97	50.93	51.13	50.91		0.06	0.14	0.16	0.08	0.47	0.04		0.08	0.10	0.02	0.41
16	50.48	50.45	50.68	50.51	50.58	50.76	50.48		0.06	0.46	0.12	0.26	0.61	0.06		0.40	0.06	0.20	0.55
	50.63	**50.58**	**50.73**	**50.71**	**50.73**	**50.69**	**50.59**	**Ave**	**0.10**	**0.28**	**0.24**	**0.30**	**0.20**	**0.01**		**0.19**	**0.15**	**0.20**	**0.11**
								Min	-0.08	0.08	0.10	0.02	0.04	-0.25		-0.10	-0.06	-0.08	-0.18
								Max	0.28	0.67	0.68	1.78	0.61	0.12		0.64	0.70	1.62	0.55
								Stand dev	0.08	0.19	0.14	0.42	0.18	0.09		0.21	0.18	0.40	0.20
								Conf 95%	0.04	0.09	0.07	0.21	0.09	0.04		0.11	0.09	0.20	0.10
								Conf 99%	0.05	0.12	0.09	0.27	0.12	0.05		0.14	0.11	0.26	0.13
								Max/min	0.18	0.30	0.29	0.88	0.29	0.18		0.37	0.38	0.85	0.37