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Factors affecting pressure resistant insulation wood fibre boards

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Preface

This Master's thesis is the final assignment for the 2-year Master's degree program in Structural Engineering and Architecture with specialization in wood technology at the Norwegian University of Life Sciences (NMBU), Department of Science and Technology (REALTEK).

The work has been carried out in collaboration with Norske Skog Saugbrugs. Together with Scandinavian Fibre Board they have developed a new type of fibreboard produced in Halden, Norway.

I wish to thank all contributors to this project. My supervisors Prof. Thomas Krinlgebotn Thiis (NMBU) and Prof. Olav Albert Høibø (NMBU) have giving me good advice and guidance during the writing process. Development Manager Dag Molteberg (Norske Skog Saugbrugs) produced and delivered the boards.

Engineer Roar Økseter has been very helpful in helping me with lab preparation for mechanical tests and PhD candidate Stergiani Charisi conducted the thermal conductivity tests. Department Manager Eirik Larnøy (NIBIO) carried out the fire tests. I'm very grateful for helpful tutoring and explanation of the different processes.

A special thanks to Olav and Dag, who have widened my knowledge on paper/fibre board production and who have always been helpful with answers to my questions.

I am also very grateful for the support from family and friends (thanks to Jonas and Christin for reviewing my work). Finally, I'm very grateful to my lovely flatmates in Dresden, who have given me feedback and support and made my stay here a happy and joyful time.

Dresden, June 2018

Hannah Skaar Amthor

Sammendrag

Denne studien undersøkte effekten av tetthet, tilsetting av leire og behandling av nanocellulose (CNF) på trefiberplater laget av Norske Skog Saugbrugs i Halden, Norge.

Bakgrunnen for produksjon av fiberplatene var at Norske Skog hadde mye fibermasse til overs som ikke kunne brukes til papirproduksjon fordi fiberen var for grov. Resultatet er en fiberplate som er laget av miljøvennlige materialer uten bruk av syntetiske bindemidler.

Platene ble produsert av termomekanisk masse (TMP). To typer fibermasse ble testet ut; en raffinert med 1100 kWh / tonn og den andre med 1600 kWh / tonn.

I alt ble 19 plater testet, 5 av dem hadde 20% leire tilsatt. 11 plater hadde en overflatebehandling av CNF og leire.

Følgende egenskaper ble testet: Tetthet, e-modul, bøyefasthet, trykkfasthet, hardhet, varmeledningsevne og brannegenskaper.

Analysen viste at tetthet, raffineringsenergi og overflatebehandling hadde en signifikant effekt for flere av de undersøkte egenskapene. Høyere energinivå (1600 kWh / tonn) ga høyere tetthetsnivåer, noe som resulterte i høyere mekanisk styrke. Type 1600 gir bedre bøyefasthet og hardhet. Ingen signifikant effekt for trykkfasthet, e-modul, varmeledningsevne og brannprøve ble funnet. Tilsetning av leire hadde en positiv effekt på brannegenskaper og ga lavere trykkfasthet, men ingen forskjell ble funnet for bøyefasthet, hardhet, e-modul og varmeledningsevne. Viresiden hadde de høyeste verdiene for e-modul, bøyefasthet og hardhet, men hadde kun en signifikant effekt for bøyefasthet og hardhet. Et tykkere lag av CNF-behandling eller CNF tilsatt i fibermassen er trolig nødvendig for å få en betydelig effekt av CNF.

Abstract

This study examined the effect of density, addition of clay and treatment of nanocellulose (CNF) had on wood fibre boards made at Norske Skog Saugbrugs mill in Halden, Norway.

The background for the production of fibre boards was that Norske Skog had a lot of fibre pulp left overs that could not be used for paper production because the fibre was too rough. The result is a fibre board made of environmentally friendly materials without the use of synthetic binders.

The boards were produced from thermomechanical pulp (TMP). Two types of pulp were tested; one refined with 1100 kWh/metric ton and the other with 1600 kWh/metric ton.

In all 19 boards were tested, 5 of them had pulp with 20 % clay added. 11 boards had a treatment combination of CNF and clay.

The following properties were tested: Density, Modulus of Elasticity (MOE), Modulus of Rupture (MOR), compressive strength, hardness, thermal conductivity and fire properties.

Analysis showed that density, refining energy and surface treatment significantly affected several of the properties investigated. Higher energy level (1600 kWh/ton) gave higher density levels which resulted in higher mechanical strength. Type 1600 provide better MOR and hardness, but no significant effect on compressive strength, MOE, thermal conductivity and fire test was found. Addition of clay had a positive effect on fire properties and gave lower compressive strength while no difference was found for bending strength, hardness, MOE and thermal conductivity. The wire side gave the highest MOE, MOR and hardness values; but had only a significant effect on MOR and hardness. A thicker layer of CNF treatment or CNF added to the pulp is probably needed to get a significant effect of CNF.

Contents

Abbreviations and definitions

RH	relative humidity (%)
MC	moisture content
R^2	coefficient of determination. Proportion of the total uncertainty that is attributed to the model fit. Values closer to 1 indicates a better fit
RMSE	root mean square error. Smaller values indicate a better fit
p-value	the probability of getting test result equal to or more extreme than what was actually observed, given that the null hypothesis is true
f-ratio	the model mean square divided by the error mean square. A high f-ratio indicates a small p-value.
N/mm^2	pressure applied by force of one newton on a surface of one square millimetre
E_m	e-modulus
F_m	bending strength / MOR
MOE	modulus of elasticity
MOR	modulus of rupture (same as bending strength)
EPS	expanded polystyrene (insulation material)
XPS	extruded polystyrene (insulation material)
polymer	large molecule or macromolecule, composed of many repeated subunits

1 Introduction

Today there is a greater demand for a more environment friendly approach in the construction industry. There is now a large focus on using other types of products in contrast to the more traditional construction materials like steel and concrete. Wood is a renewable resource and has an environmentally positive impact because it stores carbon and thereby reduces the greenhouse effect (Gobakken et al. 2014). The construction industry is a large contributor to the emission of CO_2 gases, and buildings made of environmentally friendly, renewable materials will contribute to a more sustainable environment (Sørheim et al. 2015).

There is an increased focus on building envelope components and its properties. Insulation in buildings is a critical factor to achieve thermal comfort. Insulation reduces unwanted heat loss or gain and decreases energy demands of heating and cooling systems (Kumar & Suman 2013; Tajda et al. 2016). Proper and effective use of insulation will reduce energy costs and CO_2 emissions. By prolonging the service life and increasing the use of wood materials, stored carbon will increase and thereby contribute to a positive environmental and climate effect.

A motivation for using wooden materials as insulation for buildings is their environmentally friendly aspect in contrast to other more frequently used insulation materials like EPS, phenolic foam and mineral wool. EPS and phenolic foam are derived from fossil fuel derivatives, while mineral wool is made from molten lava rock. Wood fibre board uses soft wood leftovers from sawmills and round logs not suited as raw material for the sawmilling industry. Also, wood fibre boards can be recycled if it is uncontaminated (Tingley et al. 2015). EPS is known widely for being an environmentally unfriendly material because of its big contribution to waste and plastic reserves (Kumaran & Ashrae 2006). As a plastic composite it can take up to 400 years to break down and it has a high flammability (Cosereanu et al. 2010).

1.1 Aim of Thesis

The aim of this study was to investigate properties of wood fibre boards produced by Norske Skog Saugbruks and to compare them with other relevant building materials. The following hypothesis were tested: Will an increased refining process influence the properties of the fibre boards? Will higher energy levels correlate with higher strength properties? How will the adding of clay and treatment of nanocellulose (CNF) affect the properties? Fibres that have been in the refining process with a higher energy level have achieved more delamination of cellulose fibres. A higher energy level is therefore expected to have higher strength properties.

Properties that were investigated were MOE, bending strength, hardness, compressive strength, thermal conductivity and fire properties in relation to density.

1.2 Wood fibre boards

There is a large variety of different wood-based board products. Some of them are relatively new, while others were developed before 1900 (Thoemen et al. 2010).

Wood-based fibre boards include hardboard, medium density fibre board (MDF), insulation board and wood fibre-plastic composites (WPC) among others. These products are manufactured from wood that has been refined to individual fibres or fibre bundles, which are formed into a mat, compressed, and dried. Hardboard, insulation board and MDF are usually board products used in buildings, furniture and cabinets (Shmulsky & Jones 2011). As a building material, wood has a great number of advantages. It is easily processed and added different characteristics, which makes it easy to shape into a desired product and lowers the natural variation of wood in terms of density, strength and durability. Important challenges are that wood is easy to combust and burn and that most of its properties highly depend on moisture content. In most cases, the properties will be better with a low moisture content (Tronstad 2013).

In recent years, the use of wood based materials has increased in the Norwegian construction industry, due to better high raw material utilization, more predictable material properties and a simpler processing making them suitable for prefabricated products (Solli & Glasø 2011). These factors make wood fibre boards a good alternative construction material.

1.2.1 Factors affecting wood fibre boards

Wood-based panels have a large range of engineering properties, and properties of wood fibre boards are determined by what type of wood is used, manufacturing process and additives.

Density is the most important physical index of wood and is an important indicator of strength properties (Thoemen et al. 2010). It is also the most representative index of the ignitability and combustibility of wood (Nagaoka et al. 1988).

Higher density will provide greater bonding surface between the fibres and result in stronger mechanical properties. Depending on density, wood fibre boards are divided into porous, medium-density boards and hard boards, as shown in Table 1. Wood is a hygroscopic material and density will always to some extent depend on moisture content. The density is determined by the pulp applied for panel production and the processing conditions (Lecourt et al. 2018). Boards pressed at a higher pressure will cause an increase in density.

Table 1: Different fibre boards ranged by density

Types of Boards	Density
Soft board	230-400 kg/m^3
• Insulation board	< 230 kg/m^3
• Low density board	< 400 kg/m^3
Medium density boards	500-800 kg/m^3
High density board	> 800 kg/m^3

1.2.2 Production

Wood fibre boards are produced from wood chips. The mass is sent through refining discs where the lignin in the fibre mass is softened with high temperature and pressure. The rotating disk plates are grooved and as particles move from the centre to the outer edges of the disk, they are ground to fibre bundles (Figure 1). Through this process, the fibre mass is split up into single fibres (Shmulsky & Jones 2011).

Figure 1: Refining disk used for grounding fibres and press.

There are several different manufacturing methods depending on what type of board you want to achieve. For most boards, there is a refining and mixing step which results in a pulp mixture. The mixture is then pressed into desired thickness and dried afterwards (Figure 2).

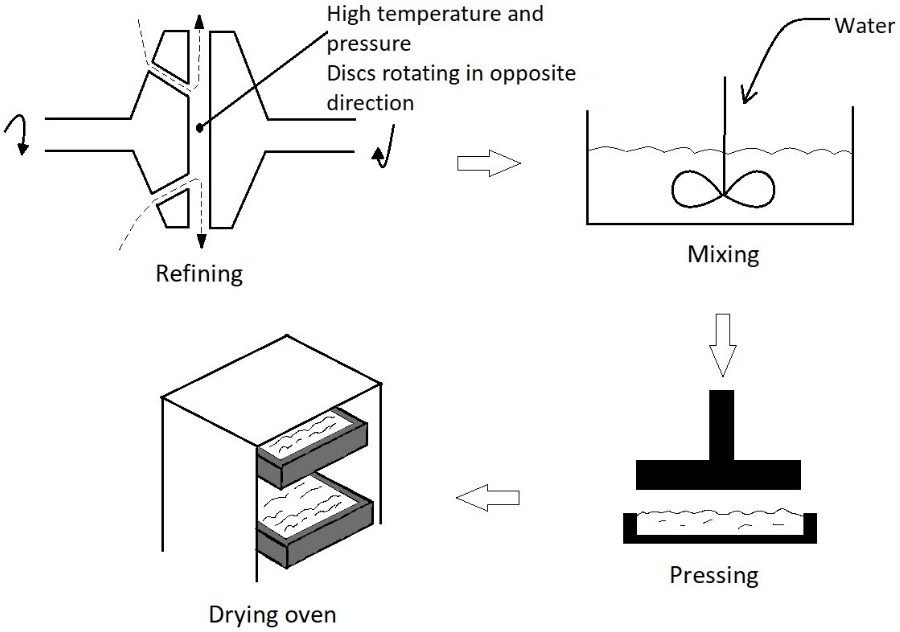

Figure 2: Schematic overview of board formation using the wet process.

1.2.3 Wet and dry process

After pulping, fibres are formed into a mat and prepressed. Mat formation is accomplished using either water or air as a forming medium, known as the wet and dry process. Wet- and dry-formed fibre board process differ exceedingly from one another, although many of the initial processing steps are common to both (Suchsland & Woodson 1987). Common for both processes is that wood is reduced to fibres through an energy demanding process (Figure 3).

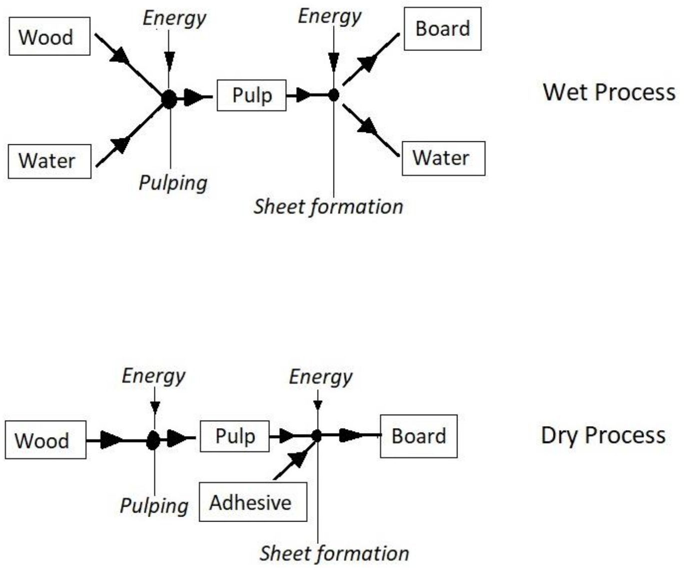

Figure 3: Simplified schematics of wet and dry fibreboard process.

The wet process is again divided into hot pressing and cold pressing. The fibre boards from Norske Skog Saugbruks were made using the wet process with cold pressing, and therefore this will be most focused on and further discussed.

According to Shmulsky & Jones (2011), pulp is mixed with water and put out on a wire screen. Water is drained away through gravity and by application of suction under the wire. The fibre mat, along with the supporting wire is moved to pre-press where excess water is squeezed out (Figure 1). Water is sewed out by pumps on the side of the machine.

1.2.4 Bonding

The production method used will also affect the type of bonding that occur in the boards. There are mainly three types of bonding; bonding with adhesives, lignin and hydrogen bonds.

Bonding with adhesives is mainly associated with the dry process and the manufacturing of medium density boards. Adhesives often used are urea formaldehyde (UF) and melamine formaldehyde (MF) (Mahrdt et al. 2015). Formaldehyde is used as a binder to enhance strength properties (Frihart 2005). Lignin bonds are mostly formed with a hot press. During hot pressing the mat is compressed at a high temperature which results in ligneous bonds. Additional water is squeezed out or evaporates. Once dried, the fibre board is finished, with a density range from 190 to 380 kg/m^3 (Hardboard and Fibreboard Manufacturing 2002). The lignin in and between the fibre is softened by heating and moisturizing, making it easier to separate the fibres by mechanical processing. During the refining process wood chips are grinded and hot steam is used to heat the fibres and thus soften the lignin. In the stock preparation step the fibres are pulped with process water for the wet formation of the boards (Runkler et al. 2003). In the case of a small amount of processing (as is the most common), lignin binding will mostly occur. This requires high heat and pressure to establish. However, it is not only the lignin that acts as a binder, there are also hydroxyl bonds (OH bonds) between the fibres and the fibrils that protrude on the surface of the fibres. The frequency of these two different forms of binding (lignin binding and OH-binding) depends on how the fibres are freed and processed. A cold press is mostly used for insulation boards. This method uses a press roll for desired thickness and then the board is dried.

The omission of hot pressing means that ligneous bonding is not achieved in insulation boards. Like in paper production, the binding forces are mainly caused by hydrogen bonds. Paper is a fibre network, which is built up from individual fibres and fibre bundles. This network forms hydrogen bonds between OH-groups on the surface of the cellulose fibres. Therefore, no artificial binders are necessary to achieve the desired board strength. A lot of water is used to produce fibre boards. The reason why so much water must be used is that the fibres must be distributed evenly on the wire where the board is formed. Water is important for providing OH-bonding as the H_2O-molecule is polar and the strength of the finished board depends on the chemical bonds that water helps build.

Normally, no glue is added to wood fibre boards. Such boards therefore have low content of formaldehyde (Treteknisk handbook 2009). Other materials (e.g. wax, clay) may be added during manufacture to improve certain properties such as stiffness, hardness, strength, durability, resistance to abrasion and moisture or fire resistance (Thoemen et al. 2010; Shmulsky & Jones 2011).

Due to the production process (cold press), the boards will have one rough and pebbled side, and one smoother side. The side with the rougher surface is known as the felt side, and the one with the finer, regular pattern is called the wire side.

1.2.5 The refining process - fibrillation

If more processed fibres are used, there will be an increased degree of fibrillation and activation of the fibre surface. Through this refining process, depending on how much energy is used for the refining discs (kwh), fibrils will protrude on the surface of the fibres (Figure 4). This means that the OH-groups become available for binding with other OH-groups. During the mixing process, it is important that water is present to form hydrogen bonds (Simmonds & Chidester 1963). More processed fibres will therefore give increased proportion of OH bonds. This will in turn increase the strength properties of the boards (Kang et al. 2006). Water is also susceptible to OH bonding to fibre, and therefore water is both important for establishing strong bonding, but water can also break them if the material is moisturized a lot (free water). The hydrogen bond network makes cellulose a relatively stable polymer, which does not easily dissolve in typical aqueous solvents and gives the cellulose chains a high axial stiffness (Eichhorn et al. 2010).

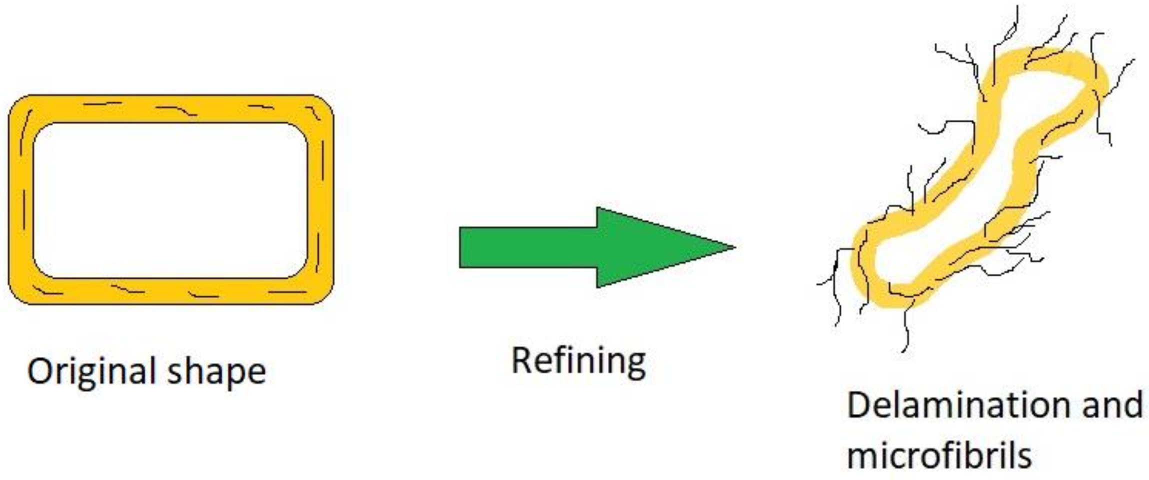

Figure 4: Delamination of a wood cell

It is possible to add external binders that increase the bonding between the fibres. These may be based on the same type of hydrogen bonds and will be affected by moisture (such as starch, nanocellulose, etc.). They can also consist of other chemical bonds where water does not have any effect. This will increase the wet strength of the boards. Additionally, substances that protect already established OH bonds (impregnation) can be added to later dehydration.

Wood fibres that have gone through a refinement on a higher energy level (in kWh) will result in a higher amount of delamination of the microfibrils. This will in turn cause strong bonding and result in stronger strength properties.

1.2.6 Additives

The most commonly used adhesives in the wood-based panel industry are amino-based adhesives based on urea-formaldehyde (UF) (Mahrdt et al. 2015). There have been concerns regarding the prospects of formaldehyde vapours that are released from insulation used in buildings. US Environmental Protection Agency (EPA) warns that exposure to formaldehyde causes respiratory difficulty, irritation of the eyes, nose and throat and in some cases cancer (Hardboard and Fibreboard Manufacturing 2002). UF-resins are made from petroleum-derived products, of which reserves are naturally limited. Also, use of UF-resins makes it difficult to recycle fibre boards (Li 2009). The European Standard aims to regulate the use of formaldehyde to reduce emissions into the environment (Riegler et al. 2012). The wood composite industry would be greatly benefited from the development of formaldehyde-free adhesives made from renewable natural resources.

Clay

Several flame retardants, used for instance in products like EPS and XPS, are considered hazardous because they contain bromine which is regarded as harmful to the environment, animals and humans because of risk of bioaccumulation. Improved fire safety through environmentally friendly and efficient methods is of industrial and scientific interest. Several studies have found that construction materials containing clay have insulating properties and may contribute to a positive indoor climate (D'Orazio et al. 2010; Toguyeni et al. 2012; Heath 2018). Liu et al. 2013 and Carosio et al. 2016 also concludes that materials mixed with clay achieve a better fire performance.

Clay is a natural resource and has become of more scientific interest because of its properties including specific surface area which results in the ability to absorb other substances, thermal stability and flame retardancy. Clay is a low cost and environmentally friendly material that will be beneficial for more use in the construction industry.

Cosereanu et al. 2010 underlines that the thermal insulating property of clay is improved approx. four times when mixing it with sawdust and suggest other natural materials with insulating properties like wool, jute and flakes. In her analysis she concludes that structures with clay had good thermal insulating properties. Better insulation in buildings will result in lower energy costs and contribute in fewer CO_2 emissions. For example, unfired clay brickwork has contributed to stabilize the indoor climate by absorbing moisture from the air at high humidity and releases moisture at low humidity (Heath 2018).

In his investigation on thermal performance of insulated roofs, D'Orazio et al. 2010 mentions the effectiveness of the air permeability of clay as a passive cooling strategy in summer which also reduces moisture in roof in winter, while the analysis of Pisello et al. 2015 shows that clay tile has a promising potential to decrease the indoor overheating in all the climate conditions with relatively low penalties in the winter months.

CNF

In the more recent years, cellulose nanofibers (CNF) have attracted considerable attention due to their promising properties. This is mainly because of their high mechanical properties (Berglund & Peijs 2010; Eichhorn et al. 2010 ; Arevalo & Peijs 2016), but also because of their biodegradability, bio-renewability, wide variety and abundant raw materials (Yousefi et al. 2018). Addition of CNF will also result in an increased interfibrillar hydrogen bonding since CNFs has a high specific surface area. Studies have investigated addition of CNF to paper and the improvement on the physical and mechanical properties of paper coated with CNF (Carosio et al. 2016), but less is known how CNF affects construction materials for industrial applications.

Clay particles will not form bonds between fibres; they will be caught up in the fibre network and result in less hydrogen bonding. They will contribute to increased density, but reduced binding. Therefore, for the same density, boards containing clay will have weaker strength properties. Clay-mixtures along with CNF is expected to have the highest strength properties.

1.3 Thermal Conductivity

An important parameter for measuring the effect of insulation materials is thermal conductivity (λ). Thermal conductivity is a specific material property and indicates the amount of heat flowing through a one-meter thick building component at a temperature difference of 1 Kelvin. The smaller the thermal conductivity of an insulating material, the greater its insulating capacity (GDI 2013). The thermal conductivity of fabricated insulating materials is influenced by the thermal conductivity of the raw materials used, the pore structure of the insulating material, the propellant, the fiber fineness- and orientation, the temperature, the behavior towards water and moisture as well as the density.

Table 2: Common insulation materials used in the construction industry with respectively λ-values.

Insulating material	λ (W/mK)
Polystyrene extruded (XPS)	0.035
Mineral wool	0.04
Polystyrene expanded (EPS)	0.04
Phenolic foam	0.02

2 Materials and methods

2.1 The wood material

2.1.1 Wood fibre boards at Norske Skog

The boards were made at Norske Skog Saugbruks Mill in Halden, Norway, from two Norway spruce thermomechanical pulp qualities. One was refined using 1100 kWh/metric ton and the other refined using 1600 kWh/metric ton. The pulp was sampled from the latency tank. The boards were made using a cold press. The mixing process was done manually with water and for some of the 1600 boards (boards made of pulp, where the refining process used 1600 kWh/metric ton) clay was added to the pulp. To get boards with different densities, the press pressure varied between 2 and 6 bars. After pressing, the boards were placed in an oven and dried at 50-60°C for 48-72 hours (Figure 5).

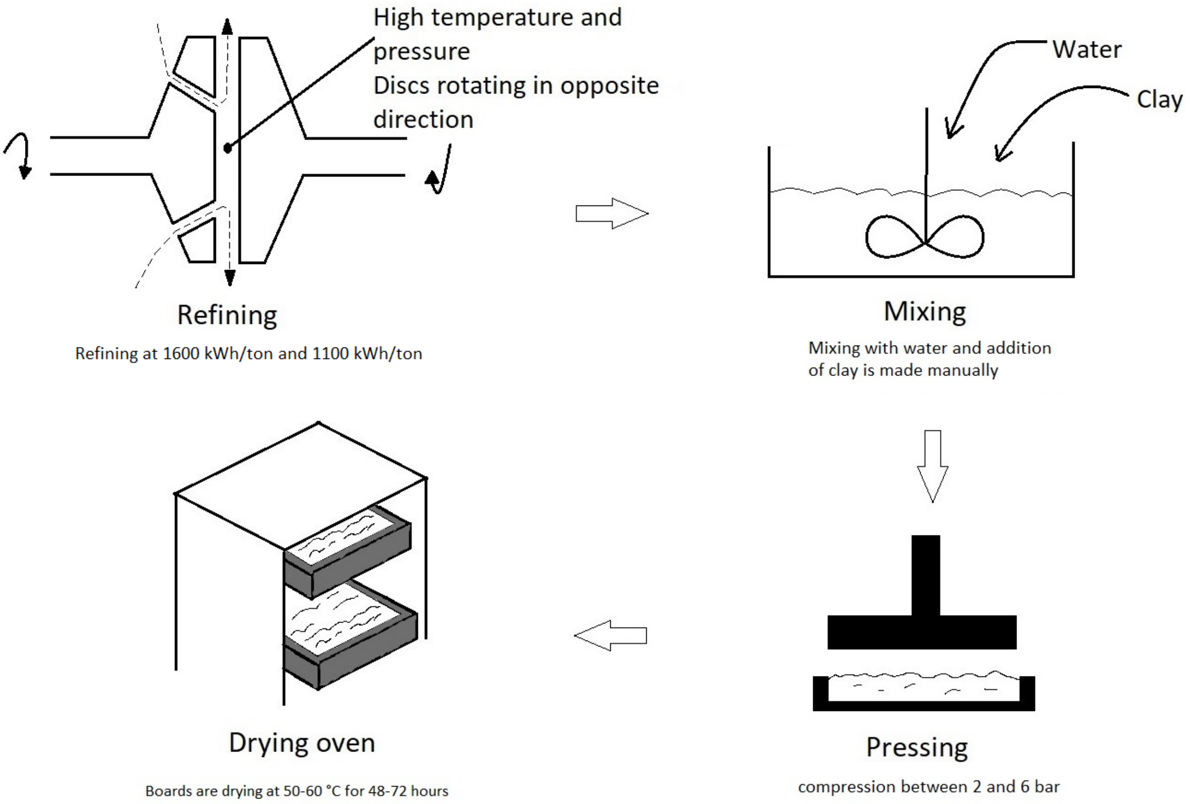

Figure 5: Production steps for wood fibre boards at Norske Skog Saugbrugs.

5 boards made of pulp refined to 1600 kWh/ton had 20 % clay mixed in. All boards had a wire side which were retained during testing. It was investigated whether energy level and clay had an impact on strength properties, thermal conductivity and fire. An overview is represented in Table 3.

Properties that were tested were; density, modulus of elasticity (MOE), modulus of rupture (MOR), compressive strength, hardness, thermal conductivity and fire properties.

Figure 6: Finished wood fibre board.

Table 3: Overview of dataset.

Board number	Board type	Additive
26	1100	No additive
30	1100	No additive
32	1100	No additive
33	1100	No additive
35	1100	No additive
59	1100	No additive
60	1100	No additive
20	1600	No additive
40	1600	No additive
42	1600	No additive
44	1600	No additive
45	1600	No additive
55	1600	No additive
58	1600	No additive
48	1600	20 % clay
49	1600	20 % clay
51	1600	20 % clay
53	1600	20 % clay
54	1600	20 % clay

Additionally, some boards were also treated with different treatments. These were boards with no clay added to the pulp. However, they were treated with nanocellulose (CNF) and clay on the surface of the board after the boards were dried. A total of 11 boards were tested with five different treatment combinations. The combinations are presented in Table 4. Only hardness, MOE and MOR were tested for the effect of treatment.

Table 4: Overview of treatment combinations. Weight calculations were delivered from Norske Skog Saugbruks.

Treatment number	Sort of treatment	Weight
0	No treatment	-
1	CNF on one side	20 g/m^2
2	CNF on both sides	30 g/m^2
3	CNF and clay (25/75) on one side	40 g/m^2
4	Wire side	-

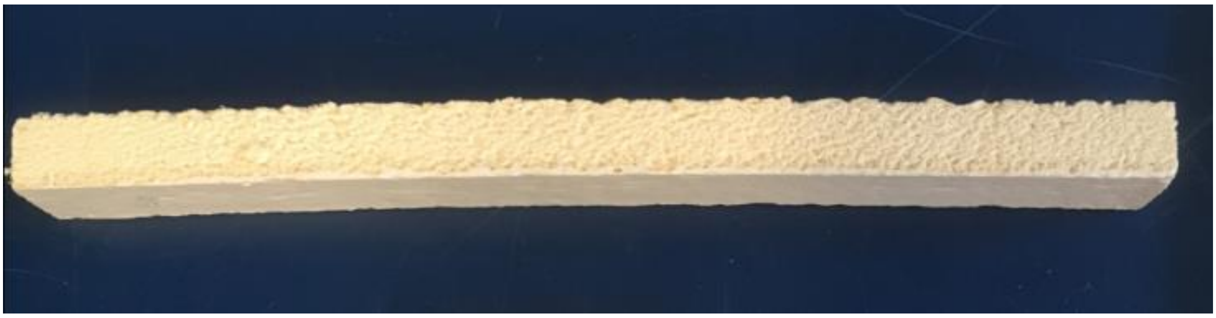

Figure 7: Test piece with CNF treatment on the underside.

2.1.2 Sampling and test piece preparation

From each board one test piece for each property was sampled, except for compressive strength and hardness. For these properties, two test pieces were sampled from each board. The average value of the two test pieces sampled from the same board was used in the statistical analysis. The test pieces were conditioned at 65 % RH and 20 °C for 4 days before testing to achieve an even moisture content equilibrium for the samples.

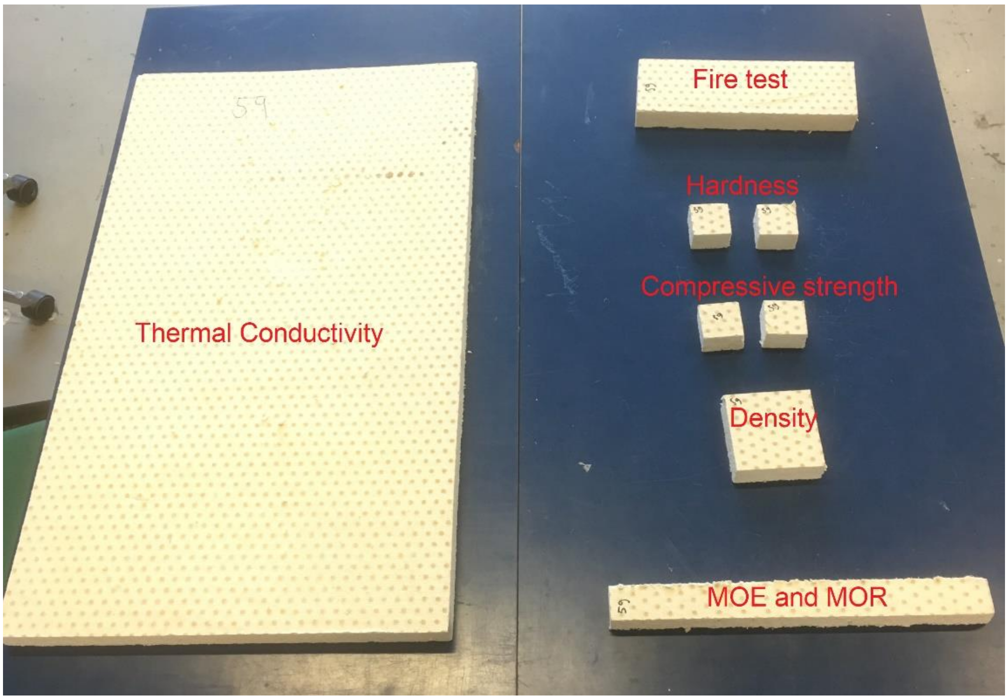

Figure 8: Test pieces (Here with the wire side facing up).

When adjusting the thickness, the wire side was kept because this side had a finer and more regular pattern than the felt side. Dimensions were measured using a Heidenhain micrometre and a slide gauge. Due to the uneven surface of the samples the measurements done with the Heidenhain gave slightly greater thicknesses than the slide gauge. With the use of Heidenhain, there will be a more even measurement between each test piece and thus less variation. All the strength tests were conducted on an Instron 5800R machine with the wire side of the test pieces/side with treatment, facing down. The only exception was the hardness tests that were conducted with the treatment facing up. Testing for MOE and MOR was done on the same testing piece. Before testing, each sample was cut down to the right size.

2.2 Density

The tests samples for density were cut down to 100x100x25 mm. A Heidenhain measurer read off at 0.01 mm precision was used to measure length, width and thickness. All the samples were first weighed and then dried at 103°C in a drying cabinet for approx. 48 hours. After drying, the dry-weight of the samples was recorded.

The moisture content was calculated using equation 1 and is expressed in percentage.

$$w_{\%} = \frac{m_w - m_0}{m_0} \times 100 \qquad (1)$$

Where

$w_{\%}$ = The moisture content of the piece given in percentage of dry weight

m_w = The mass of the test piece before drying

m_0 = The mass of the test piece after drying

2.2.1 Determination of density

Density (kg/m^3) was determined in accordance to SKANORM (1992). Calculation for density is shown in equation 2.

$$\rho_w = \frac{m_w}{V_w} \qquad (2)$$

Where

ρ_w = The density of the sample at time of testing

m_w = The mass of the sample at time of testing

V_w = The volume of the test piece by the moisture content (w) the piece had at the testing time

2.3 E-modulus and bending strength

One test sample was used to test modulus of elasticity (MOE) and modulus of rupture (MOR) for each board. The pieces were cut down to approx. 400x40x25 mm. Cross section dimensions were registered in the middle part of the test pieces with a slide gauge with an accuracy of 0.01 mm before testing.

The samples were tested in four-point bending with 360 mm spacing between the storage points and 120 mm spacing between the load points (Figure 9). Test layout was the same for MOE and MOR.

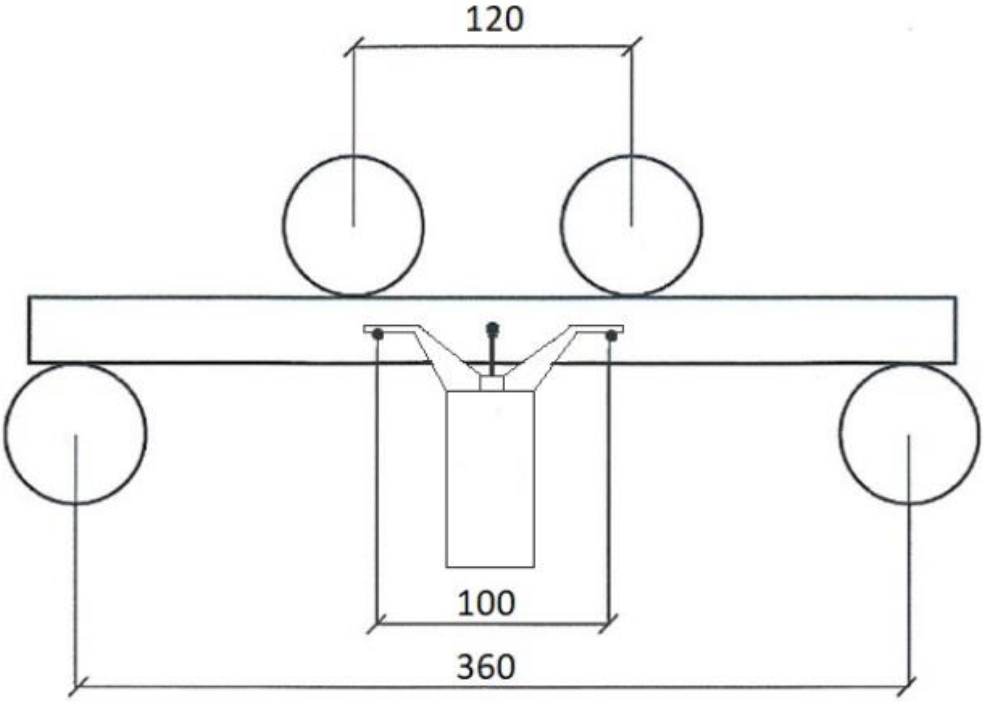

Figure 9: Test setup for MOE and MOR. All measurements are in mm.

2.3.1 Modulus of elasticity (MOE)

Local deflection was registered over a 100 mm length between the supports. The deformation measurer was attached in the neutral axis of the test pieces. A force between 3-16 N was applied in three cycles with constant velocity of 5 mm/min. For the last two cycles deflection and load was registered between 5-15 N. Each sample was tested twice, to measure the deformation on each side of the sample piece. Mean k-value was registered and used for calculation of local e-modulus according to NS-EN 408. E-modulus was calculated using equation 3.

$$E_m = \frac{3 \times a \times l_1^2}{4 \times b \times h^3} \times k - value \qquad (3)$$

Where

E_m = The E-modulus in N/mm^2 of the test piece

a = The distance between supports (a = 120 mm for this test)

l_1 = The length where deflection is registered (l_1 = 100 mm for this test)

h = The height of the test piece

b = The width of the test piece

k-value = The registered ratio between load and deflection

2.3.2 Modulus of rupture (MOR)

The testing of bending strength began right after the MOE test was completed. Load was applied with constant velocity of 5 mm/min until breach and maximal force was registered. Bending strength was calculated according to NS-EN 408 (equation 4).

$$f_m = \frac{3 \times a \times F_{max}}{b \times h^2} \qquad (4)$$

Where

f_m = The bending strength in N/mm^2 of the test piece

a = The distance between supports (a = 120 mm for this test)

F_{max} = The maximum registered load in N

b = The width of the test piece

h = The height of the test piece

After testing, a piece (ca. 500 mm) was cut off and its mass was registered and dried at 103°C for minimum two days and MC was calculated according to equation 1.

2.4 Compressive strength

Two test samples from each plate were cut down to 50x50x25 mm. The wire side was kept and the felt side was cut away when adjusting for thickness. The cross section was measured with a slide gauge before testing. Since the test pieces for compressive strength and hardness had the same size, the test samples for compressive strength was assigned number 1 and 2 (additional to their already assigned number from the factory).

A load cell with maximum load 2 kN was used. Each sample piece was pressed with a velocity of 2 mm/min, except for sample no. 33, where a velocity of 3 mm/min was used. A curve showing force vs deformation was saved for further analyses. The force vs deformation diagram was analysed in R according to SKANORM (1992).

The mass was registered after testing for all the test samples and dried at 103°C for approx. 48 hours, before dry mass was recorded. Moisture content was calculated using equation 1.

2.5 Hardness

Test dimension of the hardness samples were 50x50x25 mm. They were assigned number 3 and 4 to distinguish them from the compressive strength samples. Hardness was tested according to the JANKA method in accordance to SKANORM (1992). A steel hemisphere with radius 5.64 mm was pressed down on the wire side of the test piece with a velocity of 3 mm/min. A 2 kN load cell was used, except for test samples 33.3 and 33.4, where a 10 kN load cell of was used. The compressed area was 1 cm^2. The load was registered when the hemisphere had passed 5.64 mm into the sample. The values were registered, and a diagram was later found in R. MC was found according to the same method as used for compressive strength (equation 1).

2.6 Thermal conductivity

The experimental set up was based on the standards ISO 9869-1:2014 and ASTM C1155 – 95. Properties that was measured were thermal resistance, R, and thermal conductance Λ from surface to surface.

2.6.1 Terminology

According to ISO 9869, there is a distinction between thermal resistance R from surface to surface, and thermal resistance R_T from environment to environment. For calculations done in this thesis, thermal resistance, R, is used. R is calculated from heat flux and surface temperature. Calculation is given in equation 5.

$$R = \frac{A \cdot (t_1 - t_2)}{Q} \qquad (5)$$

Where

R = The surface to surface thermal resistance in m^2K/W

A = The metering area in m^2

t_1 = The area weighted average temperature of specimen hot surface in K

t_2 = The area weighted average temperature of specimen clean surface in K

Q = The time rate of net heat flow through the metering specimen in W

Thermal conductance Λ is the reciprocal of thermal resistance R. To determine the thermal conductance Λ or the thermal resistance R of any specimen it is necessary to know the metering area A, the net heat flow Q and the surface temperature differences Δt (Charisi 2018).

2.6.2 Technical equipment

TRSYS01 was used as measurement system. The instrument uses two heat flux plates (HFP01) along with two pairs of coupled temperature sensors. This apparatus was chosen because it is one of the most practical sensors for heat flux measurements in building physics studies and applications. By using a ceramics-plastic body, HFP01 has very low thermal resistance. The device uses a defined sensing area of $8 \cdot 10^{-4}$ m^2 (Hukseflux 2018).

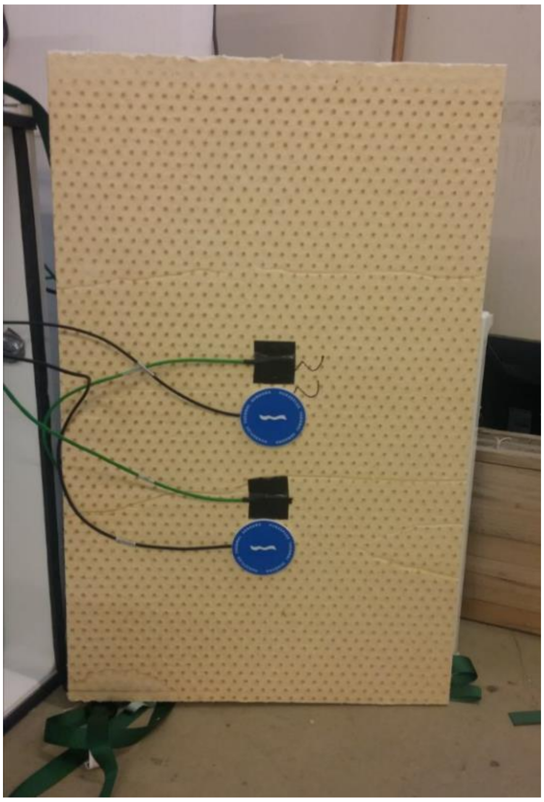

Figure 10: Wood fibre board with HFP01 fastened to it. (Photo taken by Stergiani Charisi.)

The HFP01 sensor measures heat flux, Φ, through the object in which it is connected to in W/m^2. The sensor in HFP01 is a thermopile and measures the temperature difference across the ceramics-plastic composite body of HFP01. The heat flux (W/m^2) is then calculated by dividing the HFP01 voltage output by the sensor sensitivity, S. The sensitivity is determined by the manufacturer and is provided with the calibration certificate (Hukseflux 2015).

Correction of the resistance error

When mounting the sensor on an object, its thermal resistance may significantly change the total thermal resistance of the object under observation. The resulting measurement error is called resistance error.

A first order correction of the measurement is:

$$\varphi = \frac{R_{obj} + R_{sen}}{R_{obj}} \cdot \frac{V_{sen}}{E_{sen}} \qquad (6)$$

Where

φ = The heat flux in W/m^2

R_{obj} = The thermal resistance of the object in m^{2}K/W

R_{sen} = The thermal resistance of the sensors in m^{2}K/W

V_{sen} = The voltage output of sensor in V

E_{sen} = The HFP01 sensitivity in µV/Wm^{-2}

Contact resistances between sensor and the object may contribute to the resistance error. The contact between the sensor and the object should be as small as possible, as air gaps will add thermal resistance to the sensor. The thermal conductivity of air is approximately 0.02 W/mK, almost 30 times smaller than that of the heat flux sensor. A 0.1 mm of air gap increases the effective thermal resistance of the sensor by 60%.

A high level of flux is highly recommended for the measurement of thermal resistance of walls and building materials. Strongly cooled or strongly heated rooms that create a temperature difference are optimal. To investigate the heat flux for this project, a “cold box” was assembled to create temperature difference.

A fridge was situated inside an acclimatized laboratory. The fridge was functioning at temperature approximately 4ºC (±2ºC) and RH 70% (±10%), while the lab is constantly under steady condition of 18ºC and 77.5% RH. The door of the fridge was removed and replaced by the examined wood fibre board and tightly fastened with belts (Figure 11).

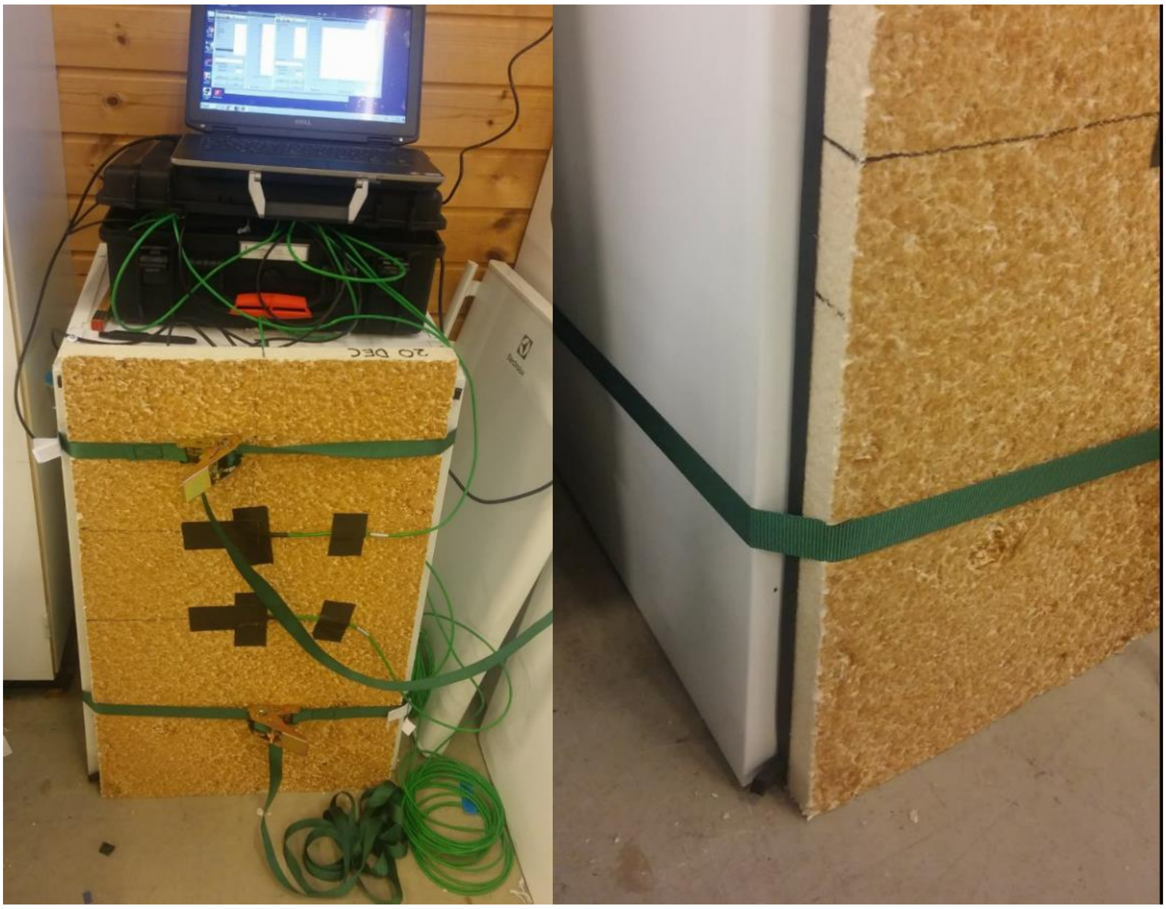

Figure 11: Test set up for measurement of thermal conductivity. (Photos taken by Stergiani Charisi.)

After each board was mounted on the fridge, the significant metering area was estimated with the help of an infrared camera, and both heat flux sensors were attached to the homogenous temperature area.

The fibre boards have an uneven surface that can easily affect the measured thermal resistance. To avoid air gaps between the sensors and the wall, a very thin double-sided tape with high conductivity was used. The red side of the heat flux sensors was attached towards the warm side of the plate, according to recommendations by the manufacturer, to generate positive output signal.

For λ-value measurements, surface temperatures were measured. Temperature sensors were placed close to the heat flux sensors (ca 1.5 cm) and attached to both sides of the plate.

Once the board was fastened to the fridge with attached sensors, the TRSYS01 started measuring the heat fluxes and the surface temperatures. ASTM C1155-95 proposes test duration for determining thermal resistance, R, of a building material should at least last for 24 hours. The experiment measurements varied for each board between 24 and 48 hours (Charisi 2018). The λ-values were registered and used for further statistical analysis.

2.7 Fire testing

15 boards were tested for fire properties at NIBIO, Ås (Table 5: Sample overview for fire tests.Table 5). Two samples from each board were tested.

Table 5: Sample overview for fire tests.

	Part 1		Part 2	
1	1100 [kWh/ton]	no clay	1600 [kWh/ton]	20 % clay
2	1100 [kWh/ton]	no clay	1600 [kWh/ton]	20 % clay
3	1100 [kWh/ton]	no clay	1600 [kWh/ton]	20 % clay
4	1100 [kWh/ton]	no clay	1600 [kWh/ton]	20 % clay
5	1100 [kWh/ton]	no clay	1600 [kWh/ton]	20 % clay
6	1600 [kWh/ton]	no clay		
7	1600 [kWh/ton]	no clay		
8	1600 [kWh/ton]	no clay		
9	1600 [kWh/ton]	no clay		
10	1600 [kWh/ton]	no clay		

The tests were done according to ISO 5660-1 and burnt with 50 KW/m² using a cone calorimeter, 25 mm away from the heat source. Before the test, the samples were conditioned at 20°C and 65% RH. After conditioning, the samples were wrapped in aluminium foil on the side and the underside before it was inserted into a mould and placed on the instrument. Testing was done in two parts and done according to the standard where they were burnt for 1800 seconds.

Figure 12: Sample example used in cone calorimeter. (Photo taken by Erik Larnøy, NIBIO, Ås)

Figure 13: Setup for cone calorimeter fire testing (Photo taken by Erik Larnøy, NIBIO, Ås)

2.7.1 Terminology

FIGRA (Fire Growth Rate) is a classification parameter used to classify the fire properties of building products (Sundström 2007). FIGRA is calculated as the maximum value of equation 7.

$$FIGRA = \frac{HRR_{max}}{elapsed\ test\ time} \tag{7}$$

Where

FIGRA is the growth rate of the burning intensity, HRR, during a test (e.g. SBI) in W/s

HRR is the total heat release rate in kW/m^2

Elapsed test time is measured in seconds

Cone calorimeter

According to a report from InnoFireWood (2005), HRR$_{max}$ is the maximum heat release rate (the first peak of a multipeak curve). Natural wood products with sufficient thickness and density are typically classified into Euroclass D. If HRR$_{max}$ < 75 kW/m^2, class B is predicted. A low FIGRA value is desirable and provides an indication of fire class for SBI testing. FIGRA < 750 W/s is criterion for achieving class D.

Restrictions of cone calorimeter

In order to decide the fire class according to the Euroclass system, an SBI test has to be used (Single Burning Item test). However, an SBI test cannot be done in small scales and is expensive to conduct while a cone calorimeter only requires a small amount of specimen material. Since the Euroclass system is standardized after SBI testing, a cone calorimeter gives only an indication of fire class.

“Time-to-ignition (TTI) is the elapsed time required to produce ignition under thermal radiation. This measurement is an important parameter to assess the fire risk of materials. A shorter TTI means it is easier for the materials to be ignited and they are at greater risk of catching fire” (Liu et al. 2013, pp. 2588).

“A higher HRR value means that the material makes more heat and affects other materials to increase the pyrolysis rate. At a high pyrolysis rate, flame spread is promoted, because more volatile combustible gases are released” (Liu et al. 2013, pp. 2589).

2.8 Statistical analysis

Analysis of covariance was used to analyse how the different factors affected the properties of wood fibre boards.

The following dependent variables were tested: Modulus of elasticity (MOE), Modulus of rupture (MOR), hardness and compressive strength. For thermal conductivity, λ was used as a continuous response variable in the analyses.

Density was used as a continuous explanatory variable and *Type* (1100 / 1600 [kWh/ton]) was used as a nominal explanatory variable in all the analyses. *Additive* (20 % clay / no clay) and *Treatment* (cnf 1 / cnf 2 / cnf + clay 1 / no treatment / wire side) were classified as categorical (nominal) explanatory variables. For fibre boards with more than one test piece of the same kind, the mean value was calculated and used for further analysis. Significance level was set to $p < 0.05$.

In order to examine the effect of clay, CNF treatment and type of energy level, the different properties were investigated separately.

The statistical analyses were performed with JMP, version 13.0 (SAS Institute Inc. 2014).

Effect of clay

As mentioned earlier, only 5 boards had clay mixed into the board and they were all of Type 1600. The most correct way to investigate if clay had effect was to study the wire side of boards with type 1600 pulp that did not have any other treatments. Statistical analysis of clay addition was made using *density, additive* and *density*additive* as variables. Normally, data are tested with center polynomials on.

“Center polynomials centres a continuous column involved in a polynomial term by subtracting the mean of each value in the column” (SAS Institute Inc. 2018).

For analysis made without center polynomials on, the effect of clay was not included as a statistical additive effect in the model. Then the regression line for samples with clay and the regression line for the samples without clay will cross the y-axis at the same place.

The same layout was made for examinations for effect of Type (*density, type* and *density*type* were used as variables) and effect of Treatment (*density, treatment* and *density*treatment* were used as variables).

To clearly illustrate the results, the statistical analysis was modelled both with and without the center polynomial function on.

Statistical analysis for fire tests

The best way to see the effect of clay on fire properties is to control the amount of remaining ash after burned sample. Clay will not burn and therefore result in a lower mass loss. Therefore, ash content was used to describe the amount of clay in the sample. Statistical analysis was performed using *FIGRA*, *HRR* and *TTI* as continuous response variables and *Ash content [%]* and *Additive* as continuous explanatory variables.

3 Results

Overall, Type 1600 had higher strength values than Type 1100. It was found a positive effect of density on all strength properties and thermal conductivity. However, for fire resistance no significant effect of density was found, only a significant effect of clay as additive.

The effect of moisture content was tested, but no significant effect on any of the properties studied was found.

3.1 MOE

3.1.1 Effect of refining energy (Type)

Density had a positive significant effect on MOE but no significant interaction effect between Density and Type were found (Table 6). Figure 14 shows that MOE increased when density increased. At high density, Type 1600 had somewhat higher values than Type 1100 (with center polynom). Without the center polynom function Type 1100 had a higher MOE (Figure 14).

Table 6: Test statistics for the factors included in the model based on data of MOE.

	With center polynom	With center polynom	Without center polynom
	Summary statistics from model step		
R^2	0.86	0.88	0.87
RMSE	16.19	15.22	15.84
Observations	58	58	58
	p values for variables in the different models		
Density	<.0001	<.0001	<.0001
Type	-	0.1815	-
Density * Type	-	0.0746	0,0666
	f values for variables in the different models		
Density	361.33	195.5833	230.3022
Type	-	1.8319	-
Density * Type	-	3.3059	3.5022

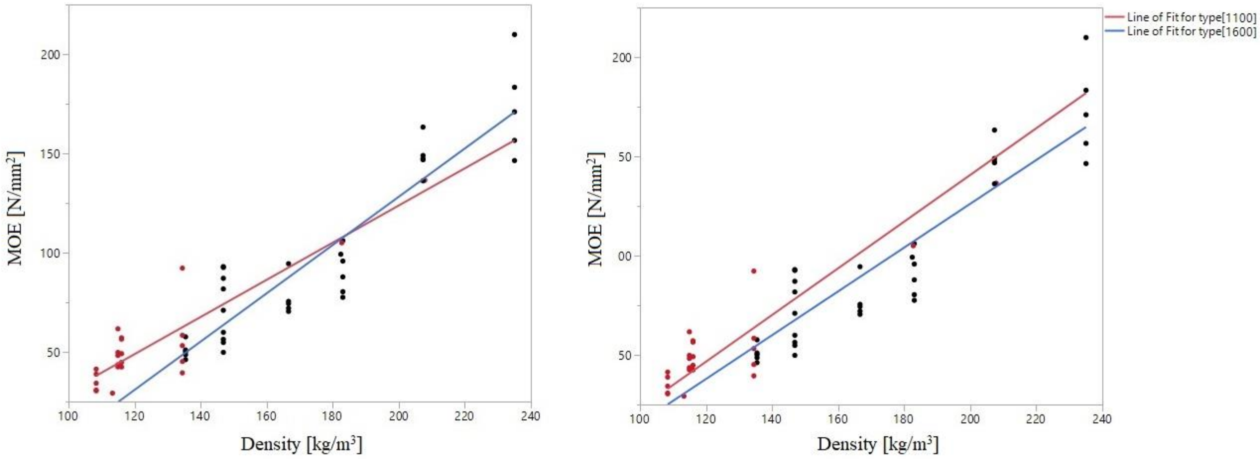

Figure 14: MOE in relation to density. Model with center polynom on the left side. Type 1100 are marked in red.

3.1.2 Effect of clay

The effect of clay as additive was almost significant (p = 0.068). Interaction between density and additive was far from significant. Figure 15 shows that samples with clay additive in average had somewhat higher MOE than those without clay.

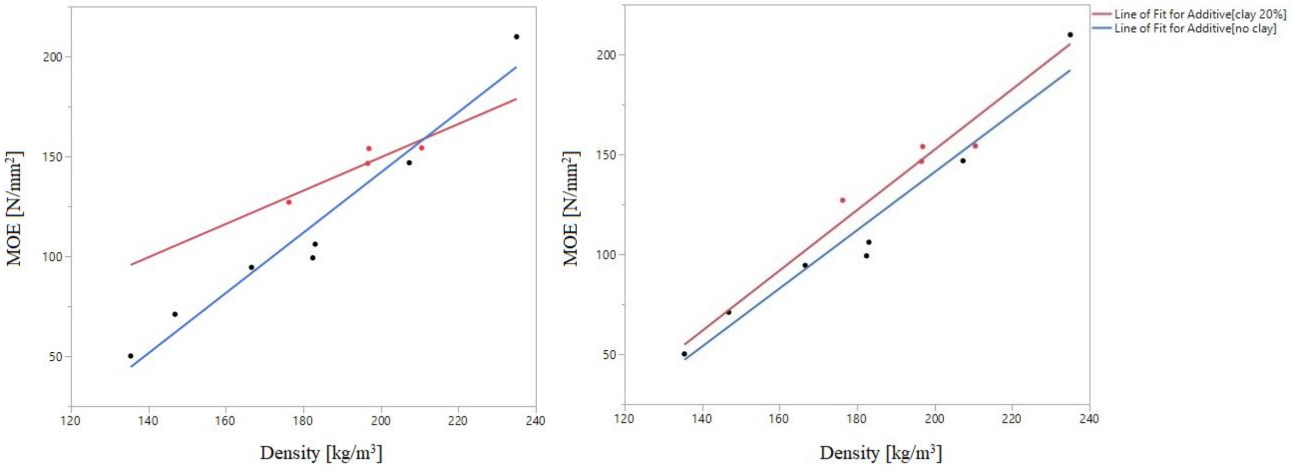

Figure 15: MOE in relation to density with clay (red line). Model with center polynom on the left side. (Only the the interaction between density an additive is included in this analysis)

3.1.3 Effect of treatment

Samples with wire side had highest MOE, followed by CNF on both sides (CNF 2) and mix of CNF and clay on one side (CNF + clay 1) (Figure 16). However, the differences were not significant.

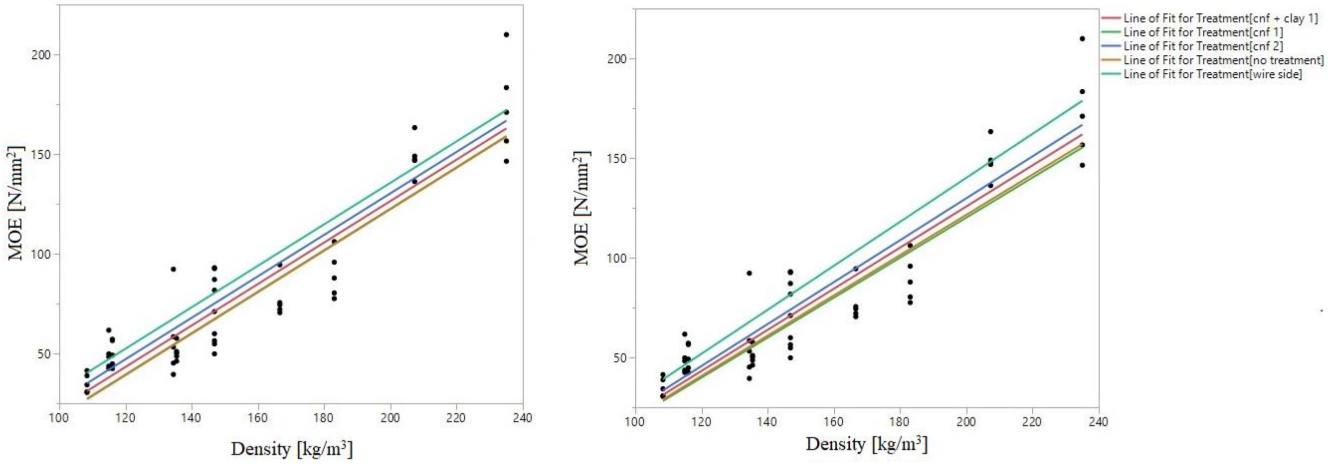

Figure 16: MOE in relation to density with treatments. Model with center polynom on the left side.

3.2 MOR

3.2.1 Effect of refining energy (Type)

Density and Type had a positive significant effect on bending strength. However, the interaction between Density and Type was not significant with the center polynom function on (Table 7).

Table 7: Test statistics for the factors included in the model based on data of MOR.

	With center polynom	Without center polynom
Summary statistics from model step		
R^2	0.81	0.81
RMSE	0.15	0.15
Observations	58	58
p values for variables in the different models		
Density	<.0001	<.0001
Type	0.0016	-
Density * Type	0.1479	0.0019
f values for variables in the different models		
Density	59.69	72.95
Type	11.00	-
Density * Type	2.16	0.0019

Figure 17Figure 17: MOR in relation to density. Model with center polynom on the left side. shows that Type 1600 had a higher bending strength than Type 1100 and bending strength increased when density increased.

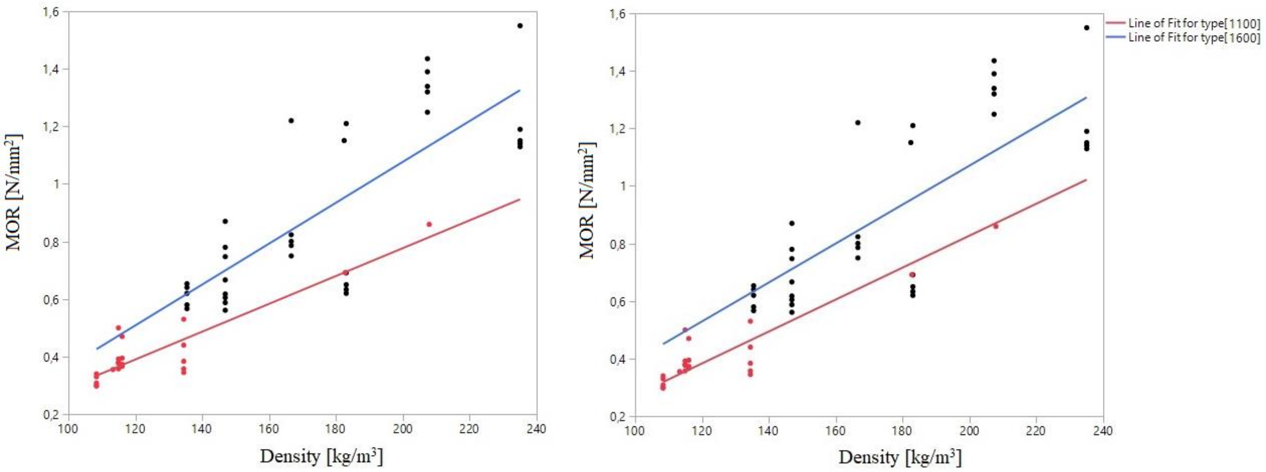

Figure 17: MOR in relation to density. Model with center polynom on the left side. Type 1100 are marked in red.

3.2.2 Effect of clay

Clay as additive had no significant effect on bending strength. Density got a $p = 0.0005$ ($R^2 = 0.75$, RMSE = 0.13, n=11).

MOR increased with density and Figure 18 indicates that samples containing clay had somewhat lower bending strength than the samples without clay.

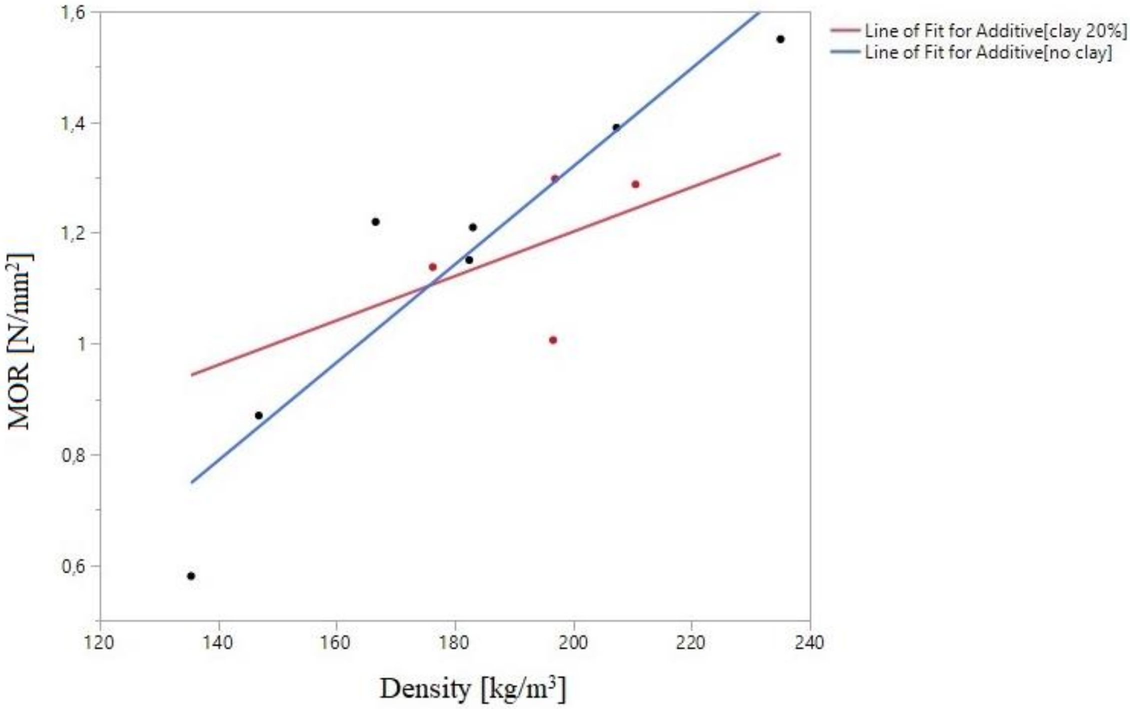

Figure 18: MOR in relation to density with clay (red line). Model with center polynom.

3.2.3 Effect of treatment

Density and Treatment had a significant effect on bending strength, but no significant effect could be found for interaction between Density and Treatment with the center polynom function on (Table 8).

Table 8: Test statistics for the factors included in the model based on data of MOR.

	With center polynom	Without center polynom
Summary statistics from model step		
R^2	0.82	0.83
RMSE	0.15	0.14
Observations	54	54
p values for variables in the different models		
Density	<.0001	<.0001
Treatment	0.0246	-
Density * Treatment	-	0.0059
f values for variables in the different models		
Density	231.130	247.19
Treatment	3.078	-
Density * Treatment	-	4.127

Samples with wire side had highest bending strength (Figure 19).

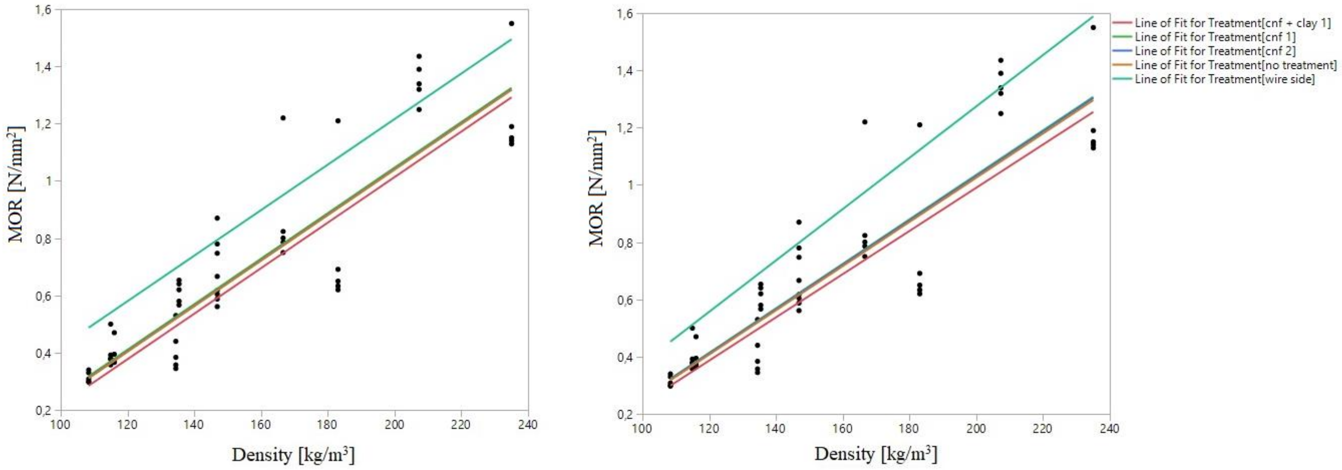

Figure 19: MOR in relation to density with treatments. Model with center polynom on the left side.

3.3 Compressive strength

3.3.1 Effect of refining energy (Type)

Only density had a positive significant effect on compressive strength (Table 9).

Table 9: Test statistics for the factors included in the model based on data of Compressive strength.

	With center polynom	With center polynom	Without center polynom
	Summary statistics from model step		
R^2	0.88	0.89	0.90
RMSE	0.039	0.037	0.036
Observations	14	14	14
	p values for variables in the different models		
Density	<.0001	<.0001	<.0001
Type	-	0.1567	-
Density * Type	-	-	0.109
	f values for variables in the different models		
Density	95.36	66.02	72.83
Type	-	2.31	-
Density * Type	-	-	3.04

Board type 1100 had a lower compressive strength than type 1600, as displayed in Figure 20.

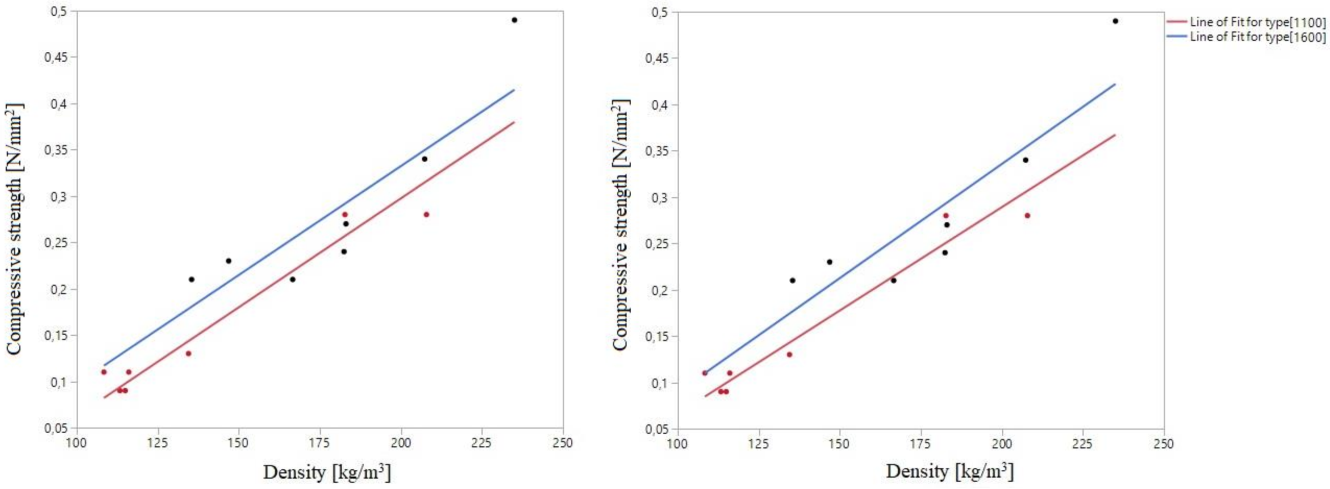

Figure 20: Compressive strength in relation to density. Model with center polynom on the left side. Type 1100 are marked in red.

3.3.2 Effect of clay

Density and Additive had a positive significant effect on compressive strength (Table 10). The interaction effect between Density and Additive was only significant without center polynom function on.

Table 10: Test statistics for the factors included in the model based on data of Compressive strength.

	With center polynom	Without center polynom
Summary statistics from model step		
R^2	0.78	0.78
RMSE	0.04	0.04
Observations	12	12
p values for variables in the different models		
Density	0.0001	0.0002
Additive	0.0126	-
Density * Additive	-	0.0129
f values for variables in the different models		
Density	40.45	38.15
Additive	9.63	-
Density * Additive	-	9.55

Addition of clay resulted in lower compressive strength (Figure 21).

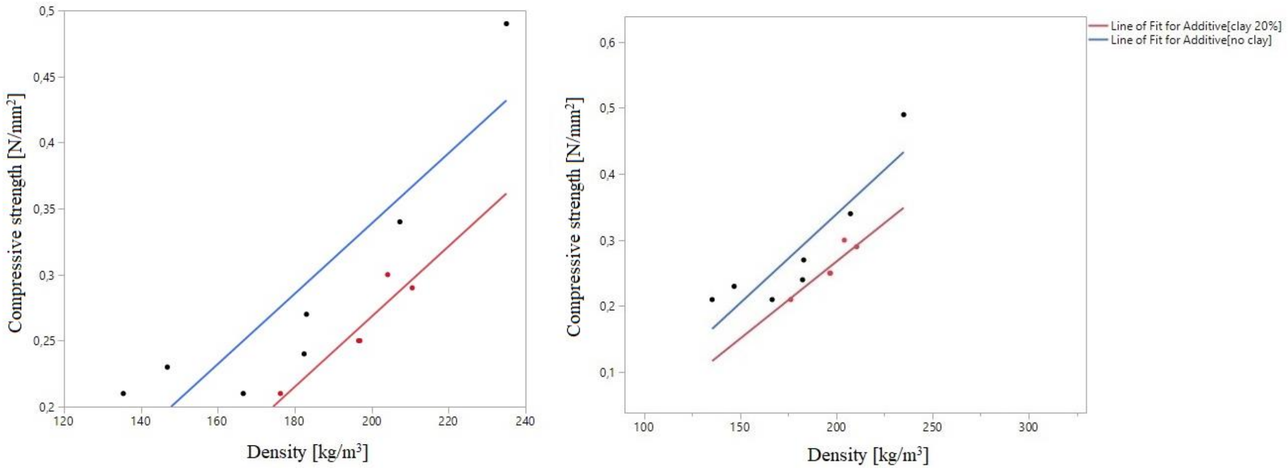

Figure 21: Compressive strength in relation to density with clay (red line). Model with center polynom on left side.

3.4 Hardness

3.4.1 Effect of refining energy (Type)

Density and Type had a significant effect on hardness (Table 11). The interaction effect between Density and Type was not significant with the center polynom function on.

Table 11: Test statistics for the factors included in the model based on data of Hardness.

	With center polynom	Without center polynom
Summary statistics from model step		
R^2	0.86	0.86
RMSE	0.37	0.36
Observations	58	58
p values for variables in the different models		
Density	<.0001	<.0001
Type	0.0015	-
Density * Type	-	0.0006
f values for variables in the different models		
Density	143.69	114.88
Type	11.22	-
Density * Type	-	13.20

Figure 22 shows that increased density and refinement energy had a positive effect on hardness.

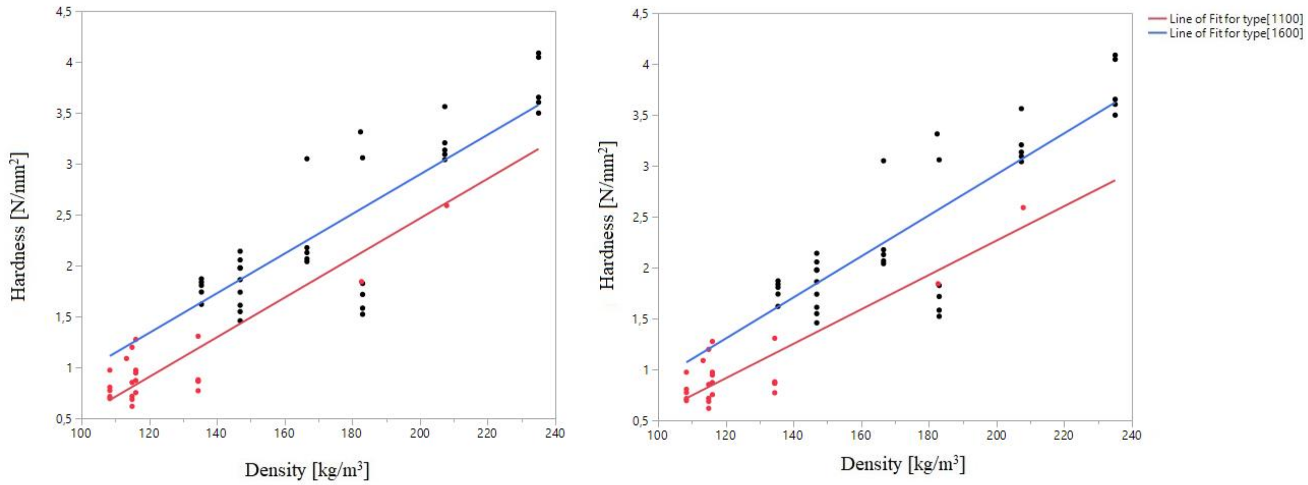

Figure 22: Hardness in relation to density. Model with center polynom on left side. Type 1100 are marked in red.

3.4.2 Effect of clay

Additive did not have a significant effect on hardness, only Density had a positive effect. The model got a R^2 of 0.87, RMSE = 0.23 and had 12 observations.

Addition of clay indicates that hardness decreases (Figure 23), but the effect is not significant.

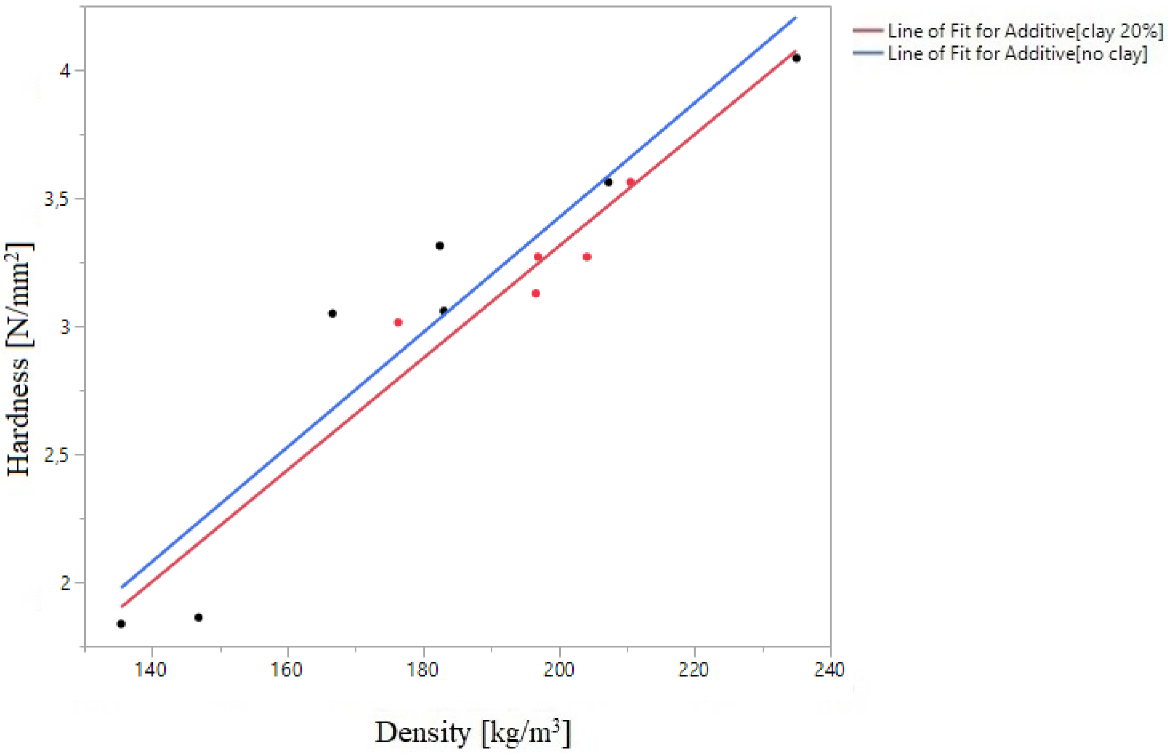

Figure 23: Hardness in relation to density with clay (red line). Model with center polynom.

3.4.3 Effect of treatment

Treatment had a significant effect on hardness (Table 12). Interaction between Density and Treatment was also examined with the center polynom function but resulted in a very high p-value.

Table 12: Test statistics for the factors included in the model based on data of Hardness.

	With center polynom	Without center polynom
Summary statistics from model step		
R^2	0.87	0.87
RMSE	0.35	0.35
Observations	54	54
p values for variables in the different models		
Density	<.0001	<.0001

Treatment	0.0133	-
Density * Treatment	-	0.0102
f values for variables in the different models		
Density	354.537	359.062
Treatment	3.52	-
Density * Treatment	-	3.72

Samples tested with the wire side resulted in highest hardness-values (Figure 24), followed by CNF-treatment on both sides and (CNF 2).

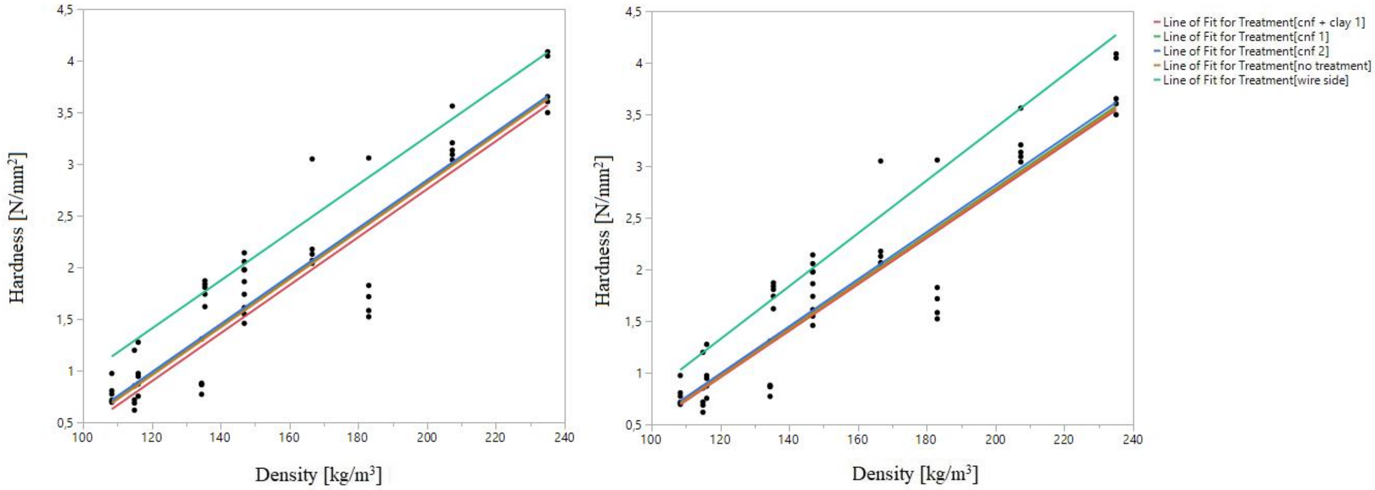

Figure 24: Hardness in relation to density with treatments. Model with center polynom on the left side.

3.5 Thermal conductivity

3.5.1 Effect of refining energy (Type)

Density had a positive significant effect on thermal conductivity ($p = 0.002$). Other variables tested were not significant. The model got a R^2 of 0.67, RMSE of 0.002. 14 observations were included in the test. Statistical analysis was also performed with Type and interaction between Density and Type but resulted in no significant effect of Type. Increased density resulted in an increased λ-value which is shown in Figure 25.

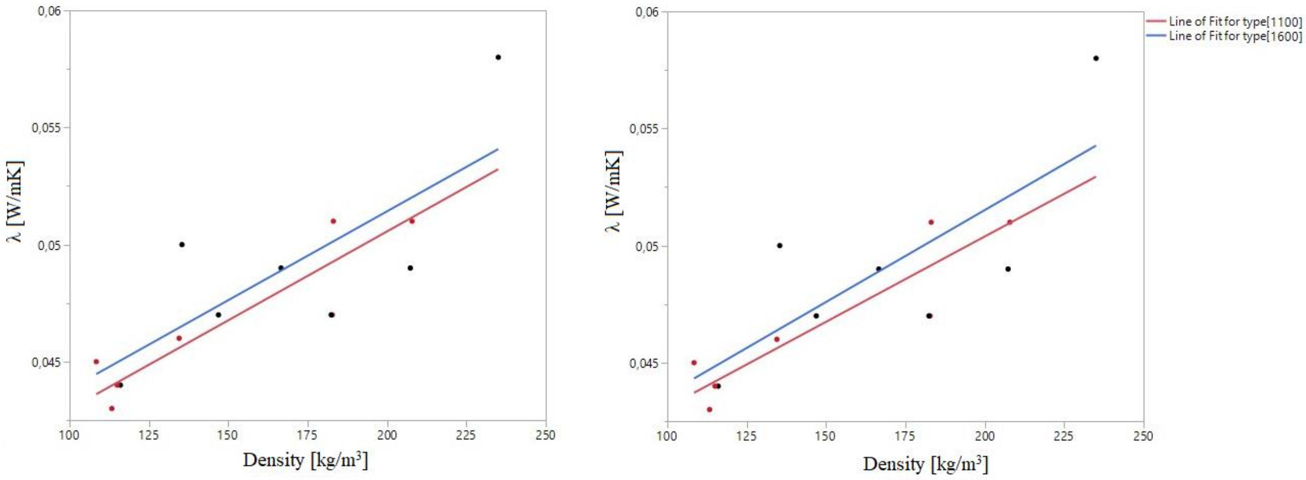

Figure 25: Thermal conductivity in relation to density. Model with center polynom on left side. Type 1100 are marked in red.

3.5.2 Effect of clay

The effect of clay was not significant (Figure 26).

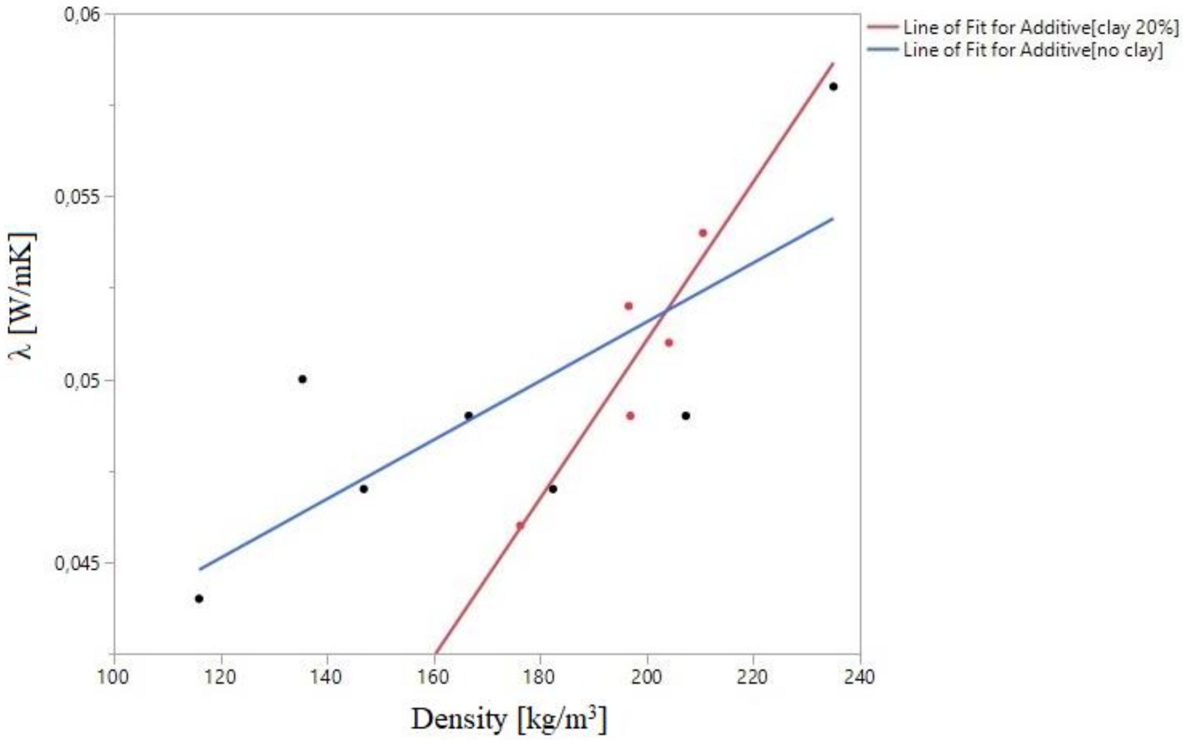

Figure 26: Thermal conductivity in relation to density with clay (red line). Model with center polynom.

3.6 Fire test

According to ISO 5660-1, the test samples are supposed to be burnt for 1800 seconds.

Procedure for part 1 was terminated since the samples had already been burnt up after 1500 seconds. Procedure for part 2 was done according to the standard and were bunt for 1800 seconds.

3.6.1 Effect of refining energy (Type)

Statistical analysis was performed using Type as variable, but no significant effect was found.

3.6.2 Effect of clay

Clay had a positive significant effect for FIGRA, HRR and TTI (Table 13). Statistical analysis was also performed with Density as variable but resulted in no significant effect.

Table 13: Test statistics for the factors included in the model based on data of Fire test.

	FIGRA [W/s]	FIGRA [W/s]	HRR [kW/m^2]	TTI [s]
	Summary statistics from model step			
R^2	0.50	0.63	0.46	0.14
RMSE	53.95	46.26	9.30	3.55
Observations	30	30	30	30
	p values for the effect in the different models			
Ash content [%]	-	<.0001	<.0001	0.0224
Additive	<.0001	-	-	-
	f value for the effect of the different models			
Ash content [%]	-	50.59	25.64	5.84
Additive	29.76	-	-	-

Addition of clay indicated a lower value for FIGRA (Figure 27 and Figure 28) and HRR (Figure 29), and a higher value for TTI (Figure 30).

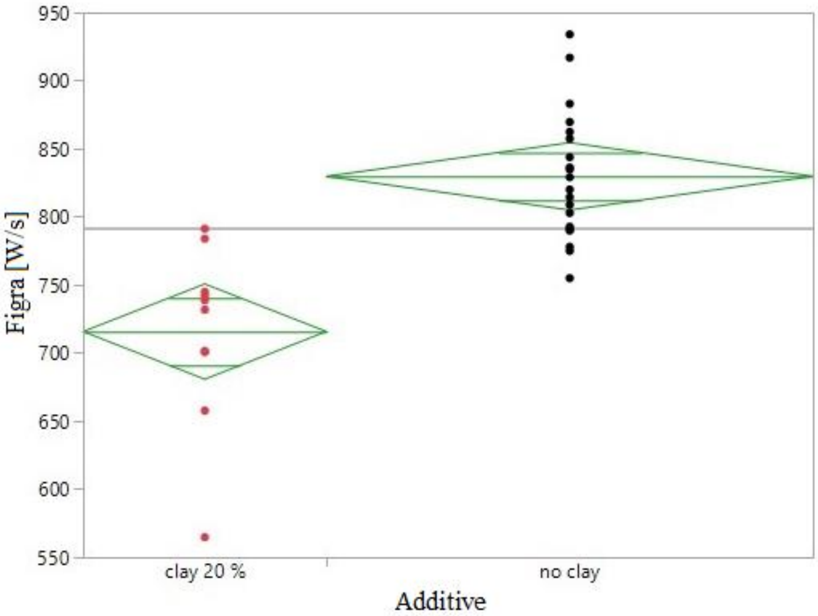

Figure 27: FIGRA in relation to additive (no clay / clay 20 %). Samples with clay are marked in red.

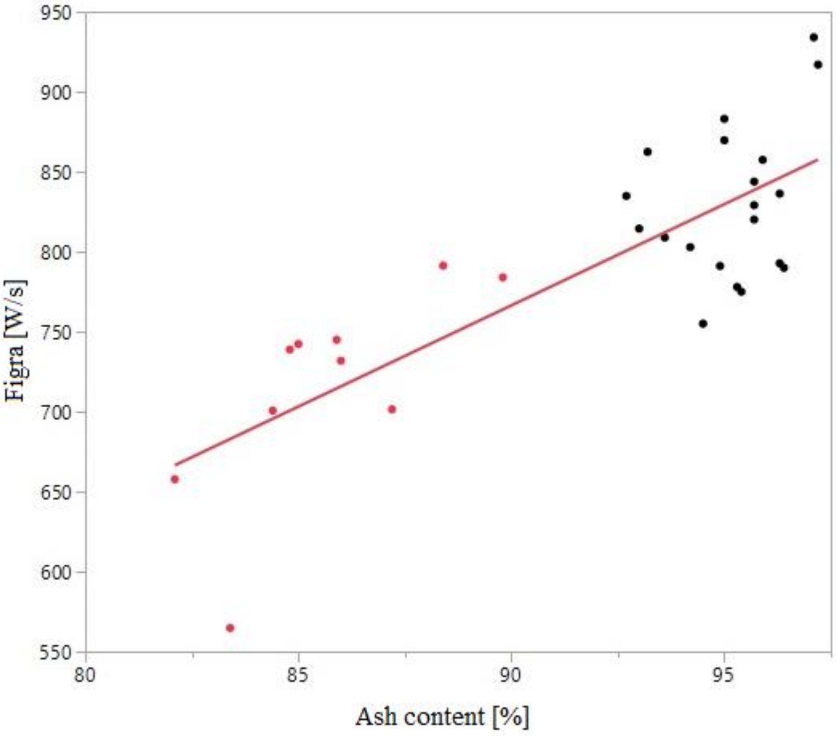

Figure 28: FIGRA in relation to ash content. Samples with clay are marked in red.

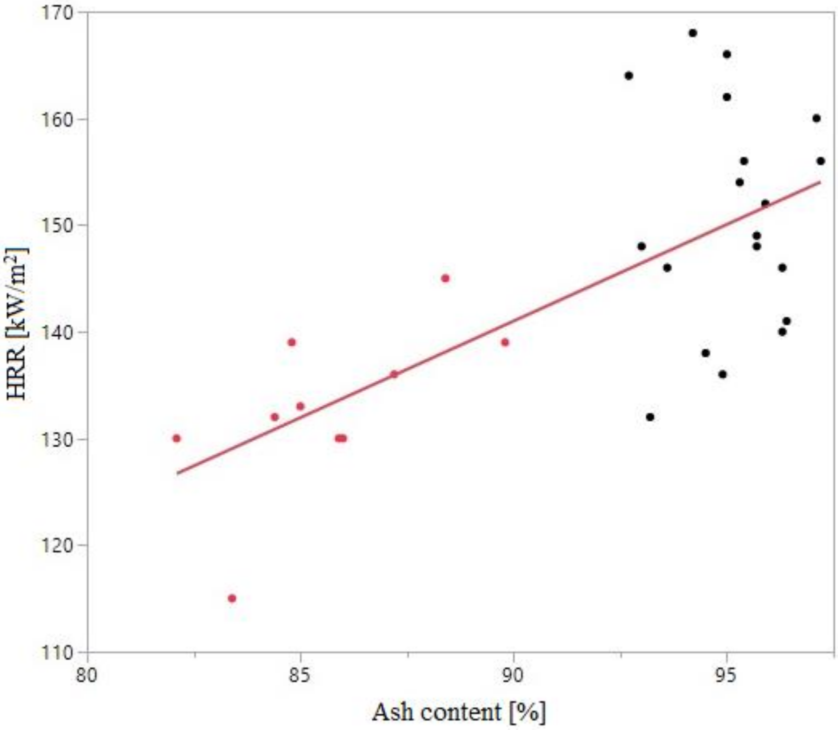

Figure 29: HRR in relation to ash content. Samples with clay are marked in red.

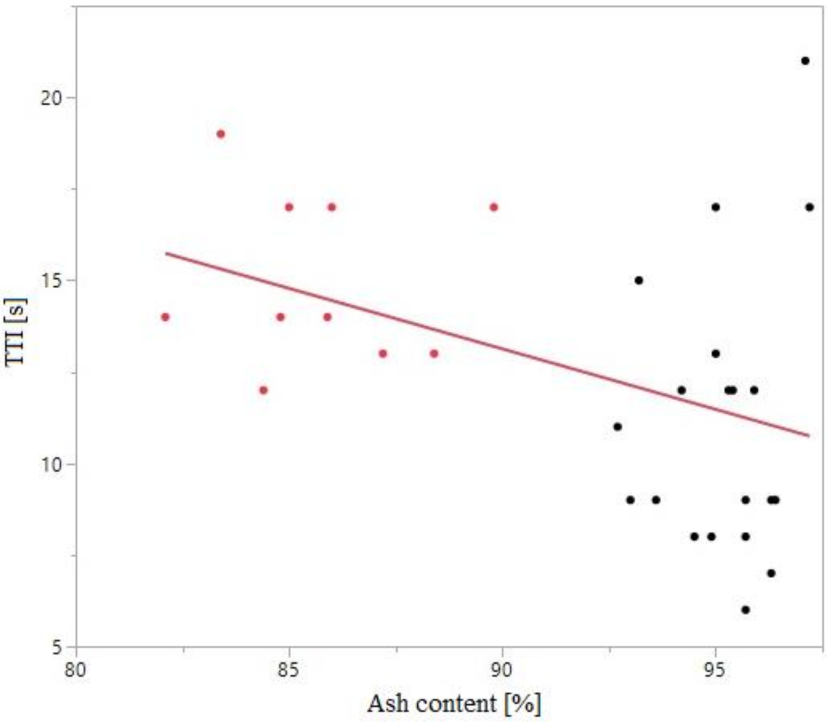

Figure 30: TTI in relation to ash content. Samples with clay are marked in red.

3.7 Summary of results

The resulting values of the wood fibre boards are listed in Table 14.

Table 14: Summary of values of the different properties tested.

Investigated property	MOE [N/mm^2]	MOR [N/mm^2]	Compressive strength [N/mm^2]	Hardness [N/mm^2]	λ [W/mK]	FIGRA [W/s]
Resulting values	30-210	0.30-1.50	0.09-0.49	0.62-4.09	0.043-0.058	564-934

4 Discussion

4.1 Strength properties

4.1.1 Effect of Type

Significant effects appeared for several factors investigated in this study. As expected, boards made with a higher energy level (1600 kWh/ton) resulted in the highest density and strength values. An increase in density resulted in an increase in strength properties and showed that *Type* was significant for almost all strength properties (Figure 17 and Figure 22). This supports earlier findings showing that fibrillation favours linkage between micro-sized fibres, supporting a network of hydrogen bonds, also providing a denser packing of the fibres (Arevalo & Peijs 2016). However, for compressive strength the somewhat positive effect of refining energy (Figure 20) was not significant.

One property did not correlate to the rest of the results. Test results for MOE were the opposite of expected (Figure 14). One challenge when measuring MOE was that some of the samples were thinner than 25 mm, which made it difficult to place them correctly in the measuring device. This may have resulted in measurements errors.

Density

Density was the most important variable affecting the properties tested, except fire properties. The pressure used when making the boards was the most important factors controlling the density. The boards were pressed with pressures ranging between 3-8 bar (1 bar = 100 kPa). This resulted in a variation in density and therefore the strength of the boards regardless of board type.

During pressing, pressure in the compressed air system will occur, leading to a lower applied pressure. In addition, the production process was done manually, making it difficult to adjust the process to a certain pressure. This may have resulted in a greater variation in board properties. There were no records from the production process regarding the exact pressure used.

Another factor that will affect the density is the thickness of the boards. For a thick board, there will be more fibres in the z-direction (the thickness direction) and the fibres will give more resistance when pressed. A thicker board will thereby result in less density. This effect will be dependent on the pressure and fibre quality (Suchsland & Woodson 1987 ; Kollmann 1955).

4.1.2 Effect of clay

Clay particles will not form bonds between fibres; they will prevent hydrogen bonding and thus contribute to reduced strength properties. Due to the high density of clay particles, the density will increase with the addition of clay under the same pressure and thickness. Measured at the same density, boards with clay will have poorer strength properties. This could be seen from the results in Figure 18, Figure 21 and Figure 23, which indicated a strength reduction for fibre boards containing clay. *Additive* did not have any significant effect, except for compressive strength (Table 11). A possible reason for this may be that there were too few samples and that the inclusion of clay was not 20 % on all samples. For MOE, the effect was opposite (Figure 15) for which the addition of clay resulted in higher strength properties. This is probably due to measurements error as mentioned earlier.

4.1.3 Effect of Treatment

The effect of treatment was only tested on MOE, MOR and hardness. There was a positive effect of wire side (Figure 16 (MOE), Figure 19 (MOR) and Figure 24 (Hardness)). This is natural since the part of the board closest to the wire probably was more compressed, leading to higher local density ant stronger bindings.

No significant effect of CNF-treatment was found. Treatment combination (clay + cnf 1) had very little effect, which was unexpected in contrast to earlier findings. Carosio et al. (2015) draws attention to the high mechanical properties of CNF and clay nanocomposites. CNF mixed with montmorillonite nanoplatelets (MTM) can be compared to mortar (CNF) and bricks (MTM) which results in a tough and ductile fibre network. The clay particles are 1-2 micrometre (diameter) and will be captured in CNF fibres and bonded to the fibre surface which forms a strong bonding network which also acts as an efficient fire protection. This is also supported by other studies (Fu et al. 2017; Zahedsheijani et al. 2012). The treatment layer was probably too thin in relation to the thickness of the board. The samples with CNF felt harder to touch, but probably their surface was too brittle.

The wire side was very stiff compared to the specimens where the wire side was cut away. Small particles will break away from the fibre particles through the refining process. The particles will be caught on the wire side and provide strong bonds. This increase both the density and the strength making the wire side the best when it comes to mechanical properties. Samples with a thicker layer of treatment or addition of a CNF mixture in the pulp is needed to study the effect of CNF on board strength.

4.2 Thermal Conductivity

The thermal conductivity increases with increasing density (Figure 25) which supports previous findings in the literature (Sonderegger & Niemz 2012) on thermal flux in soft fibreboards. No significant effect of *Type* could be seen from the statistical analysis. Other factors affecting thermal conductivity are temperature, moisture content and particle size (Sonderegger & Niemz 2009), but it was no time to investigate this further in this study.

The λ-values for the boards ranged between 0,043 and 0,058 W/mK. Here, Type 1100 had the lowest λ-values and hence was better when it comes to thermal insulation. The increased λ-value of the 1600 boards probably were due to the increase in density.

It would be interesting to test water sorption of the fibre boards, especially as this would affect the thermal conductivity (Sonderegger & Niemz 2012). Wood fibre boards are an organic and hygroscopic material that absorbs moisture from the environment. Water sorption of the fibre boards is not presented in this study.

4.2.1 Effect of clay

Since clay particles will not form bonds between fibres, they will be caught up in the fibre network and thereby contribute only to an increased density. Increased density will again lead to higher λ-values. This seems to concur with the results (Figure 26) which indicate higher density values with clay addition. However, the effect was not significant, possible due to too few samples.

4.3 Fire test

The results indicate that addition of clay has a positive effect resulting in a longer time to ignition (TTI), lower heat release rate (HRR) and FIGRA. The effect was however not good enough to give a better fire performance (6 samples resulted in FIGRA ≤ 750 W/s). There was also a great variation between the samples (Figure 27 - Figure 30).

Similar to ordinary wood, it was expected that 98 % ashes of the fibre boards would remain after the fire tests (Shmulsky & Jones 2011). There was around 95 % ash content after fire testing (Figure 28), which indicates that the fire tests were terminated before the samples were completely burned out. Clay particles are heavier than water and will make sediments. As the water used to produce fibre boards is reused, contaminations of clay may have remained in the process water. This is a source of uncertainty and clay content will therefore not be exactly 20 %. Therefore, *Ash content*, might give a better indication for clay content in the boards. A linear regression between *Additive* and *Ash content* was positive and significant (Table 13).

4.4 Limitations

There were more samples of Type 1600 than of Type 1100, which resulted in a broader dataset for Type 1600. The focus of this study was to investigate important properties and interaction, but at the same time not to conduct too many tests. Further data collection is needed to determine exactly how clay and CNF affects different properties.

No fire tests were conducted on boards with CNF treatments, but it would be interesting to see its effect given the CNF's positive fire properties in earlier studies.

Production of pulp refined with 1600 kwh/ton and CNF is fairly energy intensive and costly. In this study it was not made a cost validation of Type 1100 and 1600, which would be interesting analyse.

4.5 Evaluation of wood fibre boards from Norske Skog

The insulation efficiency of the wood fibre insulation boards is on average somewhat poorer than that of EPS. The thermal conductivity of fibre boards tested was in the interval of 0.045 and 0.058 W/mK, whereas EPS boards, it lies around 0.035 (Lassen et al. 2011). This means that a thicker layer is needed to obtain the same insulation effect as for EPS.

Wood fibre boards are a diffusion-open material; accumulated moisture can evaporate from the insulation material if the cold side of the insulation is vented. Thus, accumulated moisture of adjacent building materials will be ventilated, which is not always the case with waterproof materials such as EPS.

Challenges with wood fibre boards as an insulation material is the moisture and fire properties. Moisture in the insulation material reduces the insulation capacity, which can be caused by condensation from damp air inside the insulation materials. If not properly protected, precipitation and migration from adjoining wet materials from the ground will give moisture damage. If wood fibre boards are not kept dry, rot and mould damage will occur.

The advantage of wood fibre boards is a combination of low weight, high compressive strength, good insulation value and easy to mount. In addition, it contains no toxins and has a good environmental profile. High fibre pulp quality due to high consumption of energy makes the wood fibre boards from thermomechanical pulp a more expensive product compared to other existing insulation materials. However, the boards use less pulp than other types of fibre boards (e.g. OSB, MDF and chipboards) which makes up for energy costs. The bonding between the fibres manage to maintain a strength that is large enough to withstand relatively large external stresses and therefore does not require the use of binders such as glue (formaldehyde) to be held together.

Compared with other wood fibre boards on the marked (Bischoff Schäfer 2018), the boards from Norske Skog have higher compressive strength. The compressive strength values ranged from 0.05 to 0.2 N/mm^2 (Bischoff Schäfer), compared to 0.09 to 0.49 N/mm^2 (Norske Skog). However, the boards from Bischoff Schäfer have better λ-values, down to 0.037 W/mK.

Wood fibre boards are combustible and would probably require a covering with non-combustible materials, e.g. gypsum boards. A higher proportion of clay is necessary in order to meet national regulations and building codes. Fire retardant protection is probably necessary, especially where high fire demands are imposed, such as internal panel, doors and roof.

Applications

The boards can be produced in a variety of densities, providing a large range in properties fit for different applications. The boards can be used as insulation or as a sandwich core material in doors, walls, ceilings and floors in buildings. With a low carbon footprint, wood fibre boards make it possible to replace other less climate-friendly materials already on the market such as EPS and XPS.

5 Conclusion and further work

Type 1600 provides better bending strength and hardness. However, no significant effect on compressive strength and MOE was found. Addition of clay gave lower compressive strength, while no difference was found for bending strength, hardness and MOE. As a combustible material, fire barriers have to be applied where there are special requirements for fire classes.

Treatment had a significant effect on MOR and hardness, but not on MOE. The wire side proved to have the highest strength properties followed by a layer of nanocellulose on top and bottom side. Treatments with nanocellulose and combination of nanocellulose and clay had no significant effect on strength properties, probably because the layer was too thin.

The fibreboards are light and has relatively good mechanical properties. It has relatively high thermal insulation values and is manufactured without the use of synthetic resins or binders. This potentially leads to an environmentally friendly panel board, entirely based on renewable resources, also making them recyclable. The boards can easily be cut into a desired dimension and form and thus an increased usability. Improvement of press production can lead to a fibre board with higher mechanical properties which eventually can be used in load-bearing applications.

Proposals for further work

A study on moisture content and water sorption should be done since this probably greatly affect thermal insulation values and important strength properties.

Shear and tensile strength and sound characteristics are interesting properties that also should be tested.

No cost validation of the refinement energy levels was done in this thesis, but probably is an important factor for the profitability.

Much research is currently being done on nanocellulose (CNF) and further investigations with CNF-addition and treatments most probably would affect important structural properties.

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