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INDUSTRIAL HEMP BASED INSULATION MATERIALS AND THEIR PROPERTIES

KIUKANEPIST ISOLATSIOONMATERJALID JA NENDE OMADUSED

MASTER THESIS

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AUTHOR'S DECLARATION

Hereby I declare, that I have written this thesis independently.
No academic degree has been applied for based on this material.
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Introduction

In recent years the field of thermal protection in buildings are focusing more upon ecological properties. Environmental awareness is now not only limited to energy savings but also contained within ecologically sound construction. That is the reason why natural raw materials such as hemp, flax and others are gaining more interest nowadays. Hemp is annual bast fibre plant, which delivers fibres, shives and seeds. Bast fibres are used as raw materials for thermal insulations and shives has been mainly employed in animal bedding and construction. Hemp seeds have a high nutritional value and hemp oil has an excellent and unique fatty acid profile. They are both used for human food and animal feed. Industrial hemp can be cultivated on very different types of soils and it is considered to be one of the most sturdy and adaptable crops. Industrial hemp is universal plant, which is really easy and also environmentally friendly to grow. Usually fibre hemp is ready to harvest in four months. Hemp insulation materials also have many great properties and are user-friendly while installing them.

Firstly there is short overview about hemp cultivation and the hemp plant in general following descriptions of some common cannabis varieties grown in Europe. Secondly the pretreatments and process technology of hemp plant to hemp fibre insulation material are described. Also processes of manufacturing insulation material from hemp depending on the final product are demonstrated. In addition advantages and limitation of hemp fibre insulation products are listed. Next the directions and advice of how to install hemp insulation materials are given and suitable application areas are referred. Finally, as a practical part of current Master thesis, materials and methods of making hemp fiberboard in various methods are described and results of these readymade fiberboard properties are presented.

More precisely the description of how to make fiberboards out of hemp flour by dry and wet method is given. In addition there is an overview of cutting plan for various tests that are done on fiberboards followed by descriptions of previously mentioned tests. These tests are done for evaluating their properties, such as water absorption properties, air permeability and also tensile and bending strength. Lastly the results of these experiments are presented and analyzed.

The aim of current Master thesis is to explore the industrial hemp based insulation materials. Also to figure out hemp fibre properties that are suitable for usage in insulation material, how to treat hemp fibres to make insulation material and how much hemp fibre is needed for making insulation material. In addition there is research about what technology is needed to make hemp-fibre based insulation materials and what is the cost for making hemp fibre based insulation materials, including analysis of the results and working out the solutions.

1 Cultivation of industrial hemp

Industrial hemp has been grown in Europe for hundreds of years and it was an important crop in many European countries such as UK, Germany and Spain. Most important applications for the strong fibre were canvas for sails, sacks, canvas water hoses and fabrics as well as ropes [1].

Hemp (Cannabis Sativa L.) is annual bast fibre plant delivering fibres, shives and seeds. Its stems consist of surface layers, a bark layer with 20-50 bast fibre bundles, and a woody core with a central lumen as seen in Figure 1. Bast fibres are used as raw materials for thermal insulations, cigarette papers and biocomposites. The shive that is produced from the woody inner core of the stems has been also used as a thermal insulation, but mainly it has been employed in animal bedding and construction. Hemp seeds have a high nutritional value and hemp oil has an excellent and unique fatty acid profile. They are both used for human food and animal feed. The more precise usage of various parts of hemp plant is given in Figure 2 [1, 2].

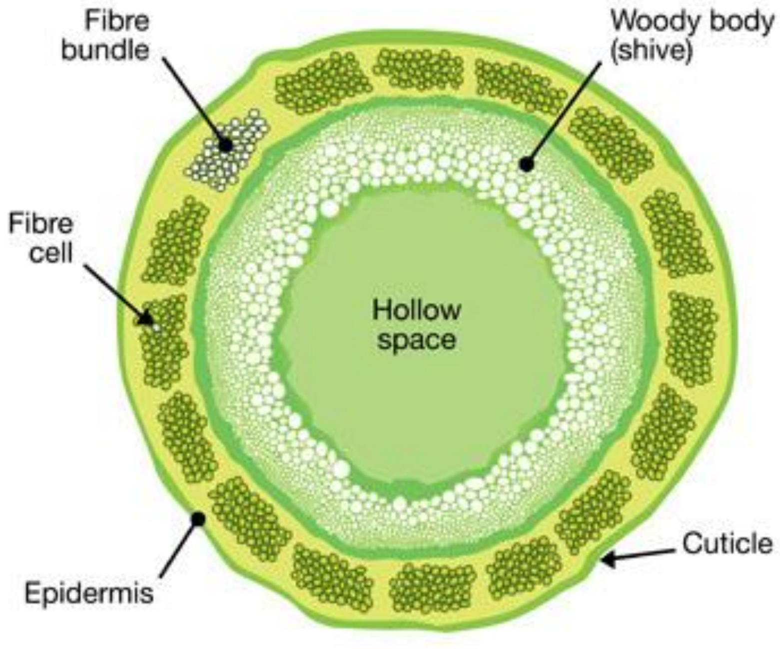

Figure 1. Cross section of hemp stalk [3]

Figure 2. Usage of industrial hemp [4]

Cannabis is divided into three species (C. sativa, C. indica and C. ruderalis), each of which has its own varieties. Cannabis is grown for fibre, oil and drug production purposes. Fibre hemp is an annual herb plant growing upto 5 m high and with a diameter from 4 to 20 mm. Fibre hemp is mainly a dioecious plant, although occasionally monoecious plants are also found. Before flowering, male and female plants are indistinguishable from each other, although they may differ somewhat in growth habit. Female plants are often shorter and have more branches than male plants. The male flowers hang in long and loose, multibranched and clustered panicles, which can be up to 30 cm long, while female flowers are tightly crowded in the axils. The difference between male and female hemp plants are seen in Figure 3. The male plants grow more quickly, which leads to uneven maturity at harvest [5].

Industrial hemp can be cultivated on very different types of soils and it is considered to be one of the most sturdy and adaptable crops. Industrial hemp is universal plant, which is really easy and also environmentally friendly to grow. Usually fibre hemp is ready to harvest in four months. The fast growing hemp plants start overshadowing the ground very quickly preventing weed from growing. Therefore maintaining the field is not necessary and hemp can grow without using any pesticides. Hemp seeds can be seeded by grain seeding machine.

Only seeds that come from certified seedsman must be used. Seeding rate depends on the purpose of hemp final use, for example fibre hemp seeding rate is about 65 kg/ha [6].

Figure 3. Female and male hemp plants [7]

1.1 Different varieties of industrial hemp

The Kompolti and USO 31 varieties are known for their high natural fibre content. They usually provide a fibre yield in range of 24 to 26%, sometimes even more [20]. USO 31 is monoecious hemp plant, which was cultivated by hemp breeders in Europe for the purpose of decreasing the psychotropic properties of industrial hemp. USO 31 matures in 125 days, which is considered early. Its stems grow up to 250 cm long and fiber content is very high (about 35%). THC content of this variety is usually less than 0,06%. Legal limit for THC concentration in industrial hemp is 0,20% according to EU legislation. Fast-ripening varieties like USO 31 are suitable for growing in northern conditions and later ripening varieties are suitable more in southern conditions. However, the late varieties are often grown in northern regions also, because the process of fiber formation finishes a month before biological ripening. This improves stem and fiber yield [8, 9].

Kompolti is the oldest dioecious variety registered in Europe (1954), nevertheless its properties meets the recent demands of cultivation. It has fine and light colored leaves and stem, which is moderately ribbed. Top of shoots are wine-red. The vegetation period is 110-

115 days from germination if it is cultivated for fiber. This variety achieves its ripeness in 150-160 days if cultivated for seed. Kompolti has great stem productivity (11-12 t/ha) and also great fiber content (31-35%). The fiber yield is among the biggest in Europe. Fiber fineness and strength are average. THC content is very low, about 0.1-0.2%. The most suitable soils for this variety are alluvial and chernozem type soils. High yield and good quality can be achieved by proper population density, sowing 3.5-4 million seeds/ha. The most suitable weather conditions for Kompolti are in continental climate zone, which includes Estonia [10].

Our Northern neighbors in Finland are also bred an industrial hemp cultivar named Finola. Finola is a short, rapidly maturing variety of hemp that was developed in 1995. Though, this variety was cultivated for the production of seed rather than fiber. Finola is grown in Canada, in several European countries, Australia and New Zealand [6, 11].

2 Hemp fibre insulation materials

2.1 Pretreatments and process technologies

Harvesting of industrial hemp takes place either in autumn when the straw is still green or in spring when the dry-line method can be used. After harvesting the bast fibres must be separated from the rest of the plant in order to be able to utilize hemp fibres. This separation has usually been achieved by dew retting or water retting following mechanical extraction processes. In the production chain of hemp fibre thermal insulations, the processing steps depend on the structure of the insulation produced [5, 12].

There are three different kinds of hemp fibre insulation materials on the market today. They are mainly supplied in rolls or as batts (in Figure 4), but also as loose fill insulation (shives) as seen in Figure 5. Loose fill insulation materials consists of unbonded fibers and are used as a blown insulation or for sealing purposes. Hemp insulation can also be in a form of rigid or semi rigid boards as seen in Figure 6.

Figure 4. Hemp insulation batts and roll [13]

Different additives such as fire-retarding and anti-fungal agents are added into the preprocessed bast fibre raw material. After that, in case of loose fill insulation, no further production steps except drying and packaging are needed. In the production of mat type insulations, the fibre material must be scribbled and binding agent must be added to ensure consistent structure and sufficient density. Finally the mat type insulations are heated and dried before packaging [5]. When it comes to board production, shives are mixed with adhesive and the fibers are thermally bonded using hot press.

Figure 5. Hemp shives [14]

Figure 6. Hemp board [15]

2.1.1 Retting

Retting is a process of removing bast fibers from the stem using enzymes from microorganisms. These enzymes break down the components that bind the fibre bundles to the other plant tissues. Retting processes can be done in two ways – on the field (dew-retting), which is based on naturally occurring fungi, or in the water (water retting), which is based on the presence of bacteria.

In water-retting the bast fibre bundles are freed from the surrounding tissue by the combined action of moisture and bacteria. The entire plant is placed in a pond letting the natural decay process remove the bark and separate the long bast fiber from the core or stick. This process can take about 2 to 3 weeks and requires large quantities of water. The quality of the bast fiber coming from water-retting is often reduced based on the mixture of organisms and from the dirty water. pH control is also important, because in most cases the pH will drop to 4.6±4.9 and a rise in pH indicates over-retting and damage to the bast fibers. The usage of clean water and specific microorganisms has been shown to greatly improve the efficiency of the retting process and also the quality of the bast fiber.

During dew-retting (in Figure 7) the retting is done in the field after the growing season is over. The cut plant is allowed to lie in the field and dew collects on it. Naturally occurring microorganisms collect on the wet plant and the biological action removes the bark and separates the bast from the core fibers. This process may take more than a month for complete fiber separation to take place. In colder climates the frost-retting can be done as following. The seeds are harvested in autumn and the rest of the plant is left in the field to be stand-retted and dried during the winter. Frost-retting results in over-retted fibres. These fibres are very absorbent and relatively resistant to moulding. Frost-retting has previously been used as a low-cost way to produce porous hemp fibre material for insulations, filters and packages.

Non-cellulosic components can also be removed from plant with chemical processes such as chemical retting or pulping. Diluted alkali or diluted acids can be used to separate fiber bundles similar to microorganism retting described before. Although microbial treatments with enzymes are preferred to strong alkaline treatments because they are often considered environmentally harmful [5, 16].

Figure 7. Hemp stalks retted for two weeks in the field [17]

2.1.2 Drying and storage

Because in Nordic climates the harvest season in autumn is often rainy it can cause problems for harvesting, retting, storage and processing of the crop. The moisture content of the autumn harvested crop may be as high as 80%. Therefore drying is needed to avoid spoilage of the crop because of moulding. If the moisture content is higher than 16% there is a risk that the retting process will continue during storage. This can deteriorate the fibre quality.

In dry line method the fibre crop is harvested in spring period, which is in Nordic climates is usually drier than in the autumn. There has been occasions when the moisture content of hemp yield were about 8-10% when harvested in spring, in this case no drying was needed. This makes the dry line method a bit more advantageous compared to harvesting in autumn. In addition the drying of stems can be accelerated if leaves and heads are stripped from the stems before cutting. The retting also affects drying, because retted stems dry at least four times faster than unretted ones [5].

2.1.3 Fractionation

In order to be able to utilize hemp fibres in industrial applications first the fibres must be separated from the rest of the plant. The bast fibre is the main raw material in the production of fibrous thermal insulations, whereas shive is usually considered as a residue or by-product. The structure of the hemp stems makes it possible to separate the fibres from the inner wooden part with a mechanical process such as scutching. Scutching is preparation of straw into stricks as seen in Figure 8. It was previously carried out manually, but the invention of the scutching mill and the scutching machine have greatly improved the process. This machine is suitable for extracting fibre from retted and also from unretted hemp stems.

Due to use of relatively short fibres in insulation materials (usually less than 15 cm) the hammer mill is used. This is very common method for the production of short fibres. In the milling process pieces of stem are crushed in a hammer mill. This process makes it easier to mix a pieces evenly or to separate fibres and shives mechanically. In the crushing process the fibres and shives are mixed together and after that can be separated by screening [5, 16].

Figure 8. Hemp stricks [18]

2.1.4 Thermal treatments

During the manufacturing process of thermal insulations the insulation mats are heated with steam explosion (STEX), because heating can prevent the growth of microorganisms. Effectiveness of the heating depends on the type of microbe, temperature and the heating period. Steam explosion (STEX) is a process in where the sample is treated with steam at high temperature and pressure. It was first developed for board production to defiberize wood into fibres. It is used for separating cellulose, hemicellulose, pectin and lignin. Fibres are both chemically modified and mechanically defiberized in the STEX process. It has been reported that the STEX process is a suitable treatment for woody hemp core, which can be purified to provide chemical grade cellulose. STEX treatment is also suitable for the processing of semi-retted hemp fibres and for flax fibres intended for textiles and composites [5].

2.2 Manufacturing depending on the final product

Decortication is the first stage of processing hemp stems, whereby the bast fibres are separated from the woody core. The bales of hemp straw are placed on the conveyor belt, where their bindings are removed. Then the bales are loosened in the bale opener and evenly fed into the hammer mills. In these hammer mills the woody core is hammered loose from the bast fibers. After that the mixture of fiber and core is transferred to the separation drum where it is sieved. The woody core is transferred to the wood cleaning section, where all dust is removed using an ingenious filter system. The fiber, which by this time has reached a purity of 90%, continues to move along on a conveyor belt to the refining line. On the refining line the raw fiber is first combed, then evenly fed into a cleaning machine. This process is repeated twice and then the fibers are pressed into bales under high pressure. The construction of this production line enables an optimum combination of fiber length and fineness to be reached [19].

From acquired fibers there are several ways to produce hemp insulation materials. For production of felts the fibers are oriented by a roller carding machine or an aerodynamic laying machine, where they are processed into a planar-arranged entity. The thin layers created by the carding machine are layered crosswise and overlapped before being worked with the first set of needles. A second set of needles continues to work the felt mats until the required thickness and density is obtained [19, 20].

For mats and boards production usually thermalbonding technology is used. Mechanically treated fibers are mixed with an appropriate proportion of a binder. A low melt synthetic fiber such as polyester, polypropylene, polylactide, polyolefin or a wet adhesive is often used as a binder. Treatments, for example flame retardants, may be applied at the mixing stage to ensure proper distribution throughout the thickness of the final product, or may be sprayed on the surface of the final product at later stages. In case of mats the next production step is carding process, where mixed fibers are combed into the same direction to create a fleece. Finally thermal bonding is processed in belt oven where prepared fleece is exposed to hot air flow or under the hot press incase of boards. Temperature of air flow depends on the matrix material [20].

2.3 Properties

One of the main global topics of current time is reduction of energetic requirements of existing and new buildings. This is important for limitation of global warming and from the point of view of sustainable development in building industry. What better way to reduce energy consumption and make building industry more sustainable than using construction materials made from natural fibers. Insulation materials based on natural fibers are progressive materials based on secondary raw materials or easily renewable raw material resources. If these materials are industrially produced, most of their parameters are comparable or better than parameters of synthetic insulating materials [21].

Hemp insulation products are perfectly natural and user friendly building materials and they don’t contain environmentally harmful additives. Producing insulation materials from hemp also helps to spare the environment by decreasing CO_2 levels in the air. During its growth, hemp absorbs greenhouse gas CO_2 from the atmosphere. This remains fixed throughout the entire life span of the insulating material, in comparison to many conventional insulating materials, which during their production release large quantities of CO_2. Another positive effect is that at the same time while hemp is extracting CO_2 from the atmosphere it also produces valuable oxygen. In addition, the whole production process of hemp fibre insulation panels requires much less energy than many conventional insulating materials. Even after installation the hemp insulation makes an ecological contribution because they don’t contaminate the indoor air. Also there is no need to treat hemp insulation materials against moths and insects because hemp fibre doesn’t contain protein [6, 22].

The insulation materials made from hemp are often completely biodegradable. They possess outstanding thermal insulation properties having the ability to store heat, generated by solar radiation as it penetrates the structure of a building, and then releasing it at a controlled rate. This leads to a much more comfortable internal living environment keeping the building warm in winter and cool in summer. Hemp insulation products also have outstanding fire resistance and sound absorption properties. All the other advantages and some limitations of natural fibre insulation materials are listed below [23].

- Advantages:
  - Hemp is a natural raw material
  - No chemical protection required during growth
  - Extremely high thermal resistance
  - It has an ability to absorb and release moisture without effecting thermal performance
  - It has a high thermal mass
  - Compatible with diffusion open construction
  - Outstanding fire protection
  - It is not affected by mould growth or insect attack as the fibre does not contain proteins
  - Easy to handle and convenient to install
  - Does not cause irritation
  - Creates a natural, healthy living climate
  - High acoustic performance
  - Renewable materials store carbon throughout usable lifespan
  - Vapour permeable

- Limitations:
  - Most products manufactured overseas and imported
  - Price currently significantly higher than oil- or mineralbased competitors
  - Requires thicker walls
  - Suitability of rendered external finishes limits application
  - Use limited to above damp-proof course or equivalent level [23, 24]

Hemp insulation is 2 to 4 times more expensive compared to glass or mineral wool. Therefore although hemp insulation gives additional benefits regarding health, moisture flow and heat capacity, only eco minded niche customers tend to choose this option [1].

Hemp cropping is still a niche branch in agriculture where special knowledge and special machinery is required. Also the raw material price is one of the most important input variables. Past experiences have shown that a close cooperation of hemp processors with the local farmers is a prerequisite for success in the long term. Straw processors need a reliable supply of high-quality straw to fulfil attractive long term contracts and farmers need reliable industrial straw purchasers to invest in special equipment for economic straw production. Without the regional cooperation of both partners the transport cost of producing hemp fibre stays as an important cost factor. Beside all that, a processing capacity of more than 2.5 t/h fibre straw and a high operational availability are essential requirements for profitable fibre production. According to the results of the economic feasibility study, modern processing plants with higher capacities could increase substantial amount of profit. But then the required investment increases up also and for the supply of such bigger processing plants, almost the double hemp cultivation area is required and higher transport costs often have to be accepted. To reduce this disadvantage the close cooperation with farmers is very important. Otherwise, the higher profit will be easily used up by higher transport cost [25].

2.4 Application and installation of hemp fibre insulation materials

In construction the industrial hemp is gained great popularity primarily in insulating houses. The main product in this area is hemp fleece. Hemp fleece is suitable for insulating new house and as well as old building floors, walls and roofs. Possible application areas are between and above rafters (in Figure 9), inserted ceiling insulation, internal and external wall insulation in timber-frame buildings and also external insulation in walls with ventilated air-condition. Hemp fleece excel in its functionality and durability and also is great at maintaining its form. Hemp fleece is available in various sizes as mats, rolls and loose fill insulation [6].

Figure 9. Woman installing hemp insulation [26]

Hemp felt is also available in different widths and thicknesses as rolls and as well as strips. Hemp felt affects room internal climate similarly as hemp fleece does. This materials ability to absorb moisture from surrounding environment and again to separate it, in case of dry air, improves the room internal climate and protects wooden covers from moisture fluctuation. The hemp fleece furnished with needles can be adjusted under the parquet and laminate floors, which are installed as suspended floors. Hemp felt strips are used for separation, partition walls and between other timber covers [6].

No special protective measures are necessary while cutting and installing hemp fibre insulation materials, because the processing of hemp insulation is particularly user friendly. It is also non-toxic and knowingly does not irritate the eyes and skin. However a small amount of dust and hemp fibres may be released during these actions. Therefore a dust mask is recommended to be worn in the process of cutting and installing. When installing hemp fibre insulation overhead, protective goggles may also be required. Blown insulation should always be carried out by an authorized contractor. As mentioned before hemp fibre insulation can be installed between rafters, ceiling joists, floor joists, partitions and stud walls as seen in Figure 10. More application areas of hemp insulation materials are given in following list:

- Roof and suspended floor:
  - External insulation, protected from the weather, below roof covering
  - Insulation between rafters, double-skin roof, topmost suspended floor
  - Internal insulation below suspended floor, below rafters or loadbearing structure
  - Below screed, without sound insulation requirements
- Wall:
  - External insulation behind cladding
  - Timber-frame and timber-panel forms of construction
  - Internal insulation to wall
  - Insulation to separating walls [23, 27]

Figure 10. Scheme of application areas [22]

The hemp insulation materials can be cut to size with hand or power saws. Small quantities of hemp insulation can be cut to size with simple cutting tools such as a long blade with a wave-like serration as seen in Figure 11. In order to make simple and uncomplicated cuts and for larger quantities, it is best to use an electric handsaw (Bosch GFZ 16-35 AC) with a wave-like serration blade - this will give the best results. The boards must be cut 10 to 20 mm oversize to assist friction fitting and they are installed into cavities using minimum pressure. Off cuts may be used to fill small voids to minimize wastage. To fill wider voids the boards must be installed in a horizontal direction [22, 23].

Figure 11. Cutting hemp fibre insulation [28]

3 Materials and methods

3.1 Materials

The raw material for making hemp boards were acquired in a form of shives from company Hempson OÜ in Saaremaa. For making fibreboard the hemp shives were grinded with separative milling by semiindustrial disintegrator DSL-115. The average particle size is 0,136 mm as seen in Table 1 and the passage amount through sieves are seen in Figure 12.

Table 1 Hemp shives grinding data

Sieves	**2,8**	**1,4**	**0,71**	**0,355**	**0,18**	**0,09**	**0,045**	**0,02**	**0,01**	**0,005**	***d50***
Particle size, mm	4,2	2,1	1,055	0,5325	0,2675	0,135	0,0675	0,0325	0,015	0,0075	
Pass amount, %	100,0	99,6	98,4	94,4	79,1	58,3	31,9	11,8	0,0	0,0	**0,136**

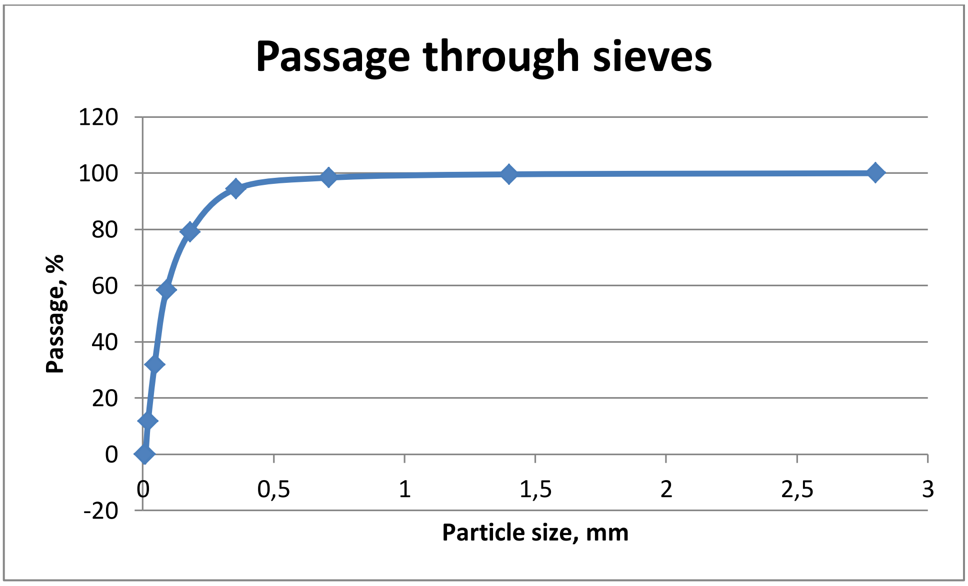

Figure 12. Particle passage through sieves

As a binder a Achema KF-FE urea-formaldehyde resin and Casco 2535 hardener were used. The Achema KF-FE physical and chemical properties are seen in Table 2 and the product information of hardener Casco 2535 are seen in Tables 3 and 4.

Table 2 Ingredient list of hardener Casco 2535

Ingredient name	Identifiers	Amount, %	Regulation (EC) No. 1272/2008 [CLP]	Type
Ammonium chloride	EC: 235-186-4 CAS: 12125-02-9 Index: 017-014-00-8	3-5	Acute Tox. 4, H302 Eye Irrit. 2, H319	Substance classified with a health or environmental hazard and workplace exposure limit
1,2-benzisothiazol-3 (2H)-one	EC: 220-120-9 CAS: 2634-33-5 Index: 613-088-00-6	0.0015 - 0.05	Acute Tox. 4, H302 Skin Irrit. 2, H315 Eye Dam. 1, H318 Skin Sens. 1, H317 Aquatic Acute 1, H400	Substance classified with a health or environmental hazard

Table 3 Physical and chemical properties of hardener Casco 2535

Physical state	Liquid
Color	Grey
Odour	Faint odour
pH	3,5 to 5,5
Initial boiling point	100 °C
Density	1,45 g/cm^3
Solubility	Miscible in water
Viscosity	2000 - 10000 mPas (25 °C)

Table 4 Physical and chemical properties of urea-formaldehyde resin Achema KF-FE

Appearance	Whitish liquid
Mass fraction of non-volatile substances	67±1%
Relative viscosity	75 - 140 s
pH	7,5 - 8,7
Consolidation time at 100 °C	40 - 60 s
Adhesive bond strength	10 N/mm^2
Coagulation ratio	(1:2)-(1:8)

For covering fiberboards with kraft paper also Penosil EN 2014/D3 Water resistant PVA glue was used. This glue consists 100 % of water-based dispersion polymer - vinyl acetate-ethylene and its properties are shown in Table 5 [29].

Table 5 Physical and chemical properties of used PVA glue [29]

Physical state at 20 °C	Liquid
Color	White
Boiling point at atmospheric pressure	100 °C
Density at 20 °C	1 kg/m^3
Melting point/freezing point	0 °C
Flash point	Non flammable (> 60 °C)

3.2 Methods

3.2.1 Dry method hemp fiberboard

For producing hemp fiberboards the grinded hemp chaffs were used as raw material and urea-formaldehyde resin (67% dry matter content) was used as an adhesive. Adhesive was prepared for all three boards separately. Amount of adhesive for one board was calculated based on following: 340 g hemp flour (moisture content 8%) was meant for one board and amount of resin is 11% from hemp flour dry matter. Hardener was added to the urea-formaldehyde resin in the amount of 2% from dry matter of resin and diluted in the amount of added water. Adhesive content was diluted to 55% by adding water. At the same time adhesive is prepared, the hotpress should be switched on to achieve the temperature needed for pressing (110°C). Adhesive calculations for each board are following:

Mass of hemp shives (moisture content 8%) = 340 g

Mass of hemp shives dry matter = 340 x 0.92 = 312,8 g

Amount of resin = 312,8 x 0,11 = 34,408 g

When adhesive has 67% dry matter, then mass of adhesive = 34,408 x 100./.67 = 51,355 g

Hardener amount = 34,408 x 0,02 = 0,7 g

Water amount = 34,408 x 100 / 55 = 62,56 g

62,56 – 51,355 = 11,21 g => 11,21 ml

Next the 340 g of hemp flour was placed into mixer. First the mixer was switched on and then the prepared adhesive was dropped slowly into the mixer. After the adhesive was added the mixing continued for 3 minutes as seen in Figure 13. After that mixer was stopped and the mixture of hemp flour and adhesive was removed.

Figure 13. Mixing the hemp flour with adhesive

Then the mat forming frame was placed on the pressing plate and filled with a mixture of hemp flour and adhesive. First the mixture was pressed by hand and then the frame was removed. Thickness calibators were placed on the edges of pressing plate to fix the thickness of the board. Formed mat was covered with the pressing plate and placed into hot pre-heated press. Hotpressing was done for 5 minutes at 110°C and at maximum pressure (90 kg/cm^2). The mat forming process and readymade fibreboard are seen in Figure 14. Altogether 19 fiberboard were made by dry method.

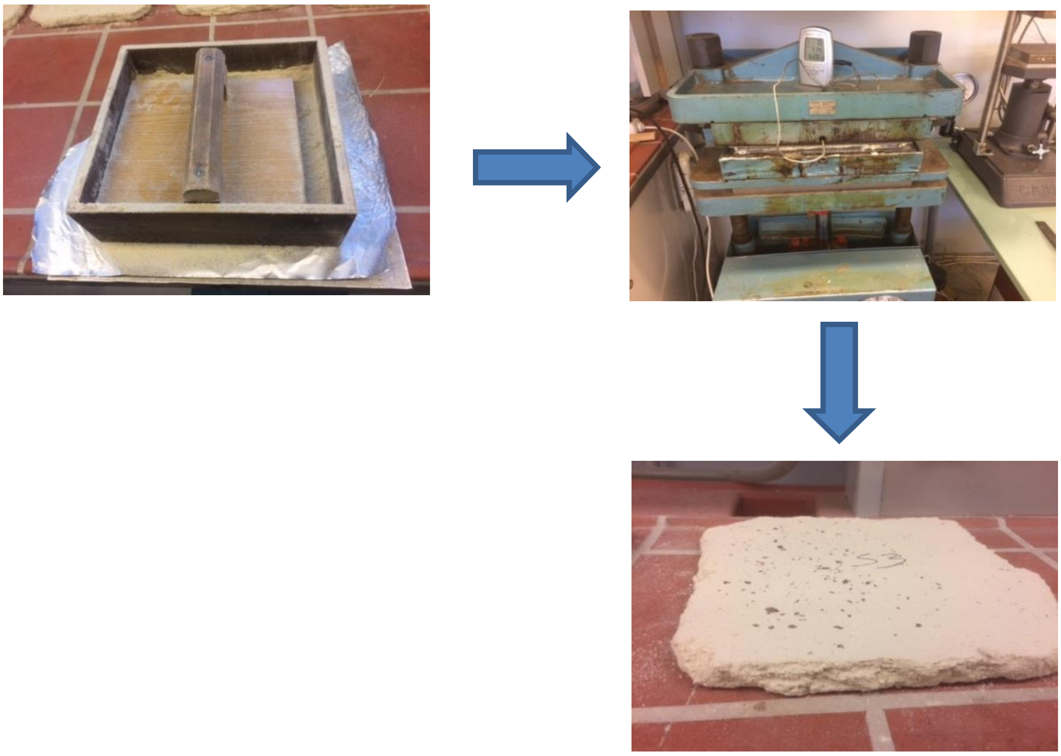

Figure 14. Prepressing, hotpressing and readymade fibreboard

According to manometer the pressure on the hydraulic system of the hotpress was recorded and based on pressure, dimensions of the fibreboard and diameter of the hydraulic silinder (100 mm) the pressure load was calculated. Table 6 shows all the pressing results.

Calculation of the pressure load for a first sample as an example is following:

Force = Pressure x Area

Cylinder diameter = 100 mm = 0,1 m

Cylinder area = $\pi \times r^2 = \pi \times 0{,}05^2 = 0{,}00785\ m^2$

Average pressure of 79 kg/cm^2 = 7,742 MPa

Cylinder Force = 7,742 x 0,00785 = 0,061 N

$$Pressure\ load = \frac{\text{Cylinder Force}}{\text{Plywood Area}} = \frac{0{,}061}{0{,}0484} = 1{,}26\ MPa$$

The pressure loads for all 19 fibreboards are shown in Figure 15. The average pressure load was 1,19 MPa and the highest was 1,26 MPa.

Table 6 Pressure load

Sample	**Used pressure (max), kg/cm^2**	**Used pressure (min), kg/cm^2**	**Average pressure, kg/cm^2**	**Pressure load, MPa**	**Temperature range, °C**
1	82	76	79	1,26	104-114
2	80	72	76	1,21	102-110
3	77	67	72	1,14	120-128
4	87	71	79	1,26	102-115
5	85	67	76	1,21	114-129
6	83	65	74	1,18	127-137
7	75	63	69	1,10	107-118
8	87	70	78,5	1,25	104-115
9	85	68	76,5	1,22	119-133
10	79	65	72	1,14	124-131
11	88	71	79,5	1,26	115-128
12	82	67	74,5	1,18	117-124
13	80	65	72,5	1,15	115-130
14	83	65	74	1,18	120-125
15	75	62	68,5	1,09	111-125
16	87	70	78,5	1,25	104-116
17	80	66	73	1,16	118-129
18	85	66	75,5	1,20	112-120
19	80	63	71,5	1,14	107-118

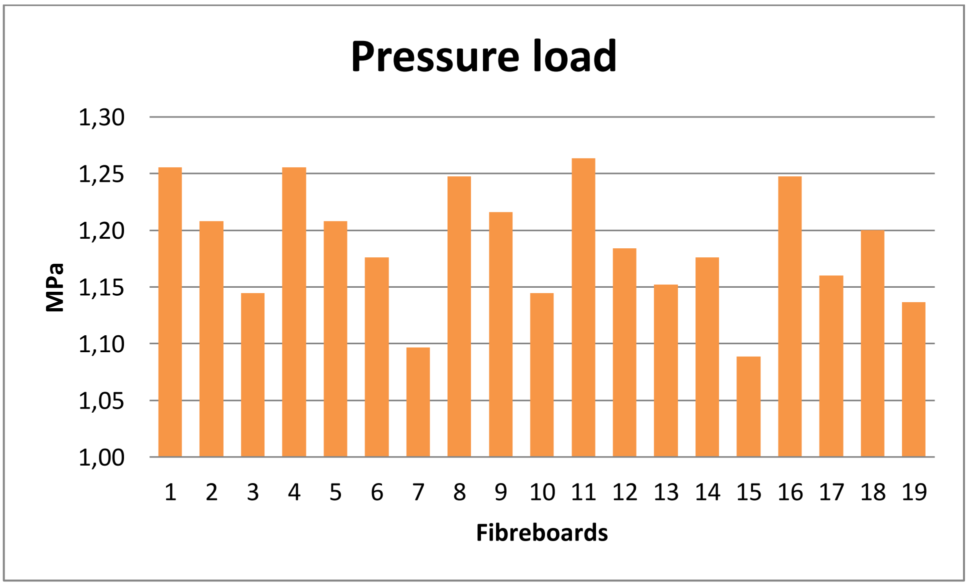

Figure 15. Pressure loads used for fibreboard samples 1 to 19

3.2.2 Covering fiberboards with kraft paper

For covering fibreboards with kraft paper 30 paper pieces with measurments 20x20 mm were cut out. Cut out papers were weighted with technical scale (Mettler Toledo, d = 0,01 g) before and after the gluing (Figure 16) to find out glue consumption. Then the papers were glued on the both sides of fiberboard. Next, in case of papers glued with UF resin, the covered fiberboard were placed under hot press for 5 minutes at average temperature of 110°C. In case of gluing with PVA the fiberboards were placed under cold-press for 5 minutes. In either case the pressure of hydraulic press were minimum – 20 kg/cm^2.

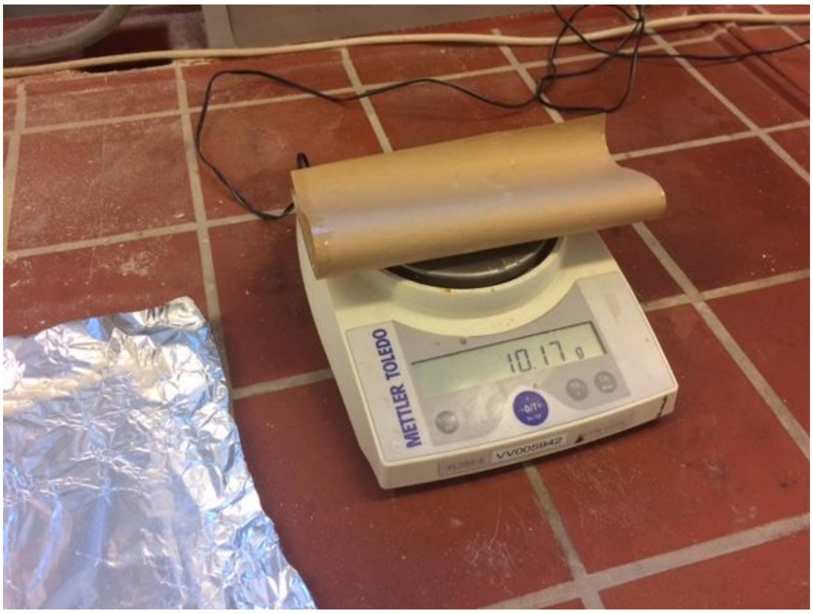

Figure 16. Weighting after gluing

Altogether six fiberboards were covered using PVA glue as seen in Figure 17 and nine of them were glued with urea-formaldehyde resin. Three covered fibreboards, which were glued with UF resin came out cracked as seen in Figure 18. Cracking may have occured due to repeated contact with high temperature. Cracked fiberboards were not used during experiments. Glue consumption of both adhesives are seen in Table 7 and 8. The average consumption of PVA glue per one board were 15,21 g and the average consumption of UF were 12,99 g.

Table 7 PVA consumption

Sample		Sheet 1		Sheet 2		Glue consumption, g		
		Mass without glue, g	**Mass with glue, g**	**Mass without glue, g**	**Mass with glue, g**	**Sheet 1**	**Sheet 2**	**Total**
PVA	1	3,91	12,7	3,91	11,79	8,79	7,88	16,67
	2	3,93	11,61	3,91	11,13	7,68	7,22	14,9
	3	3,84	12,22	3,9	13,56	8,38	9,66	18,04
	4	3,83	11,9	3,88	11,32	8,07	7,44	15,51
	5	3,81	10,55	4,02	10,15	6,74	6,13	12,87
	6	3,98	11,44	3,91	9,73	7,46	5,82	13,28
							Average	15,21
							Total	91,27

Table 8 UF consumption

Sample		Sheet 1		Sheet 2		Glue consumption, g		
		Mass without glue, g	**Mass with glue, g**	**Mass without glue, g**	**Mass with glue, g**	**Sheet 1**	**Sheet 2**	**Total**
UF	1	3,84	8,91	3,84	9,78	5,07	5,94	11,01
	2	3,91	9,42	3,92	10,28	5,51	6,36	11,87
	3	3,87	11,31	3,91	11,31	7,44	7,4	14,84
	4	3,98	11,68	3,95	9,36	7,7	5,41	13,11
	5	3,89	9,08	3,89	11,38	5,19	7,49	12,68
	6	3,82	9,75	3,93	10,38	5,93	6,45	12,38
	7	3,86	10,82	3,9	11,27	6,96	7,37	14,33
	8	3,93	10,17	3,9	11,73	6,24	7,83	14,07
	9	3,89	10,25	3,92	10,15	6,36	6,23	12,59
							Average	12,99
							Total	116,88

Figure 17. Adding PVA glue to kraft paper

Figure 18. Cracked fiberboard

3.2.3 Wet method hemp fibreboard

For producing softboard already grinded hemp chaffs are used. Board forming is made using handsheet former LA-1 what is commonly used in paper industry laboratories as seen in Figure 19.

For one board 150 g pulp with dry matter content of 91% is needed. First the pulp is mixed with water in a mixer and then the pulp will be poured to sheet former's drainer cylinder. After that the mixed pulp will be diluted up to volume of 8 to l in the sheet former's drainer cylinder. Diluted pulp is mixed manually for 3-5s to homogenize the concentration following the instant water draining.

Formed mat is then placed between perforated plates and pressed in hydraulic press at room temperature with pressure 20 kg/cm^2 for 5 minutes. Pressed softboards as seen in Figure 20 are dried in the drying oven at 103 ºC for 24 h. For each fiberboard a pulp concentration in cylinder is calculated as follows:

Mass of pulp dry matter = 150 * 91% = 136,5 g

Volume of water = 8 L = 0,008 m^3

Pulp concentration = mass of pulp dry matter/volume of water

Pulp concentration = 136,5 / 0,008 =17062,5 g/m^3

The pulp concentration for every fiberboard made by wet method are shown in the Table 9.

Table 9 Pulp concentration of fiberboards

Sample	**Pulp concentration, g/m3**
Softboard 1	17062,5
Softboard 2	17062,5
Softboard 3	17062,5
Softboard 4	17062,5
Softboard 5	17062,5
Softboard 6	17062,5

Pulp concentration was the same for all the fiberboards – 17062,5g/m^3, which makes it approximately 17 kg per 1000 L. It shows that manufacturing fiberboards by wet process requires a lot of water.

Figure 19. Handsheet former

Figure 20. Board before drying

3.2.4 Test plan

Cutting plans of various experiments and the specimens measurements are depicted in Figures 21 and 22 and the amount of specimens for various tests are shown in Table 10. Classification of different test specimens is following:

1 - Bending strength
2 - Axial withdrawal of screws
3 - Tensile strength perpendicular to the plane
4 - Swelling
5 - Air permeability

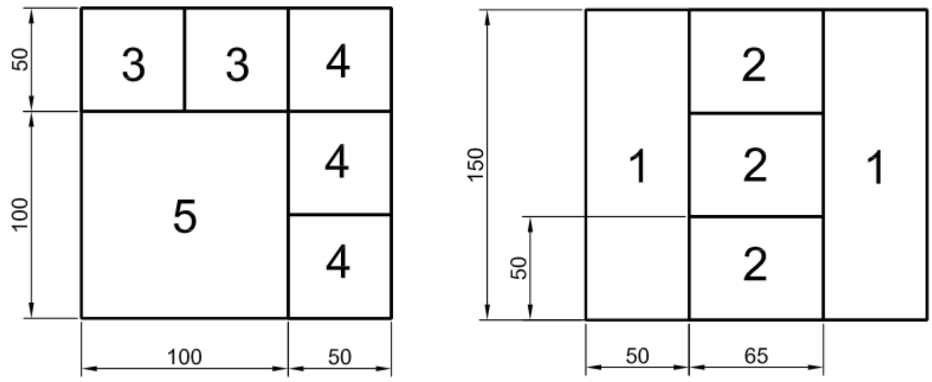

Figure 21. Cutting plan for fiberboards made by dry method

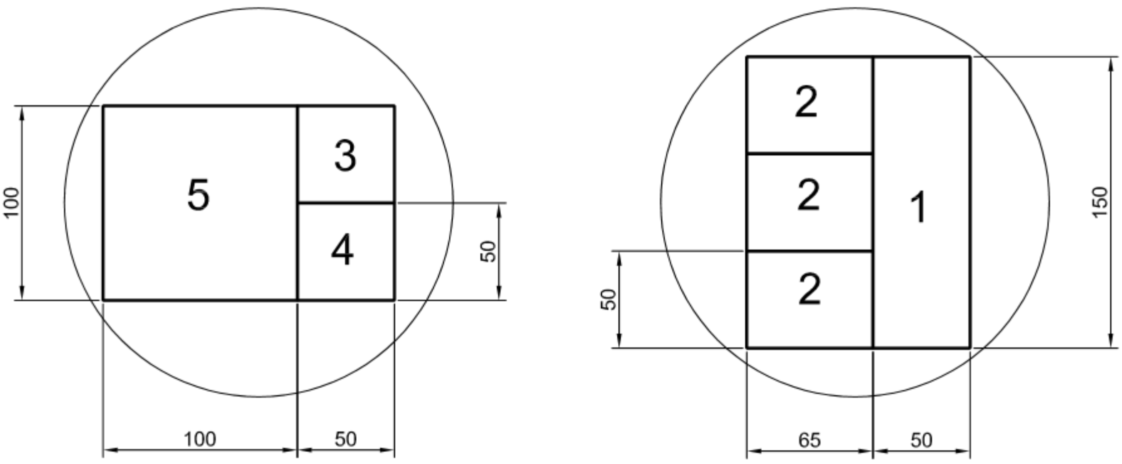

Figure 22. Cutting plan for fiberboards made by wet method

Table 10 Amount of specimens for various tests

Method	**Boards, pcs**	**Bending strength (150x50 mm), pcs**	**Axial withdrawal of screws (65x50 mm), pcs**	**Tensile strength (50x50 mm), pcs**	**Swelling (50x50 mm), pcs**	**Air permeability (100x100 mm), pcs**
Dry	4	5	5	5	4	1
Dry (UF)	6	5	5	-	-	1
Dry (PVA)	6	5	5	-	-	1
Wet	6	5	5	5	4	1

3.2.5 Determining density

Determining density of building applications such as thermal insulating products can be done in accordance with standard EN 323:2002. The density is determined as the ratio of the mass and the volume of the given sample.

For this experiment 4 test specimens made by dry method and 4 test specimens made by wet method with measurements (50 x 50 mm) were used. The dimensions of the specimens were measured with caliper (d = 0,01 mm) to an accuracy of 0,5 %. After that the volumes of the specimens from these measurements were calculated. Each specimen were weighted with technical scale (Mettler Toledo, d = 0,01 g) to an accuracy of 0,5 % and its mass in kilograms was recorded. Finally the density, ρ in kg/m^3, was calculated using the following formula:

$$\rho = \frac{m}{V}$$

where

m is the mass of the test specimen, in kg;

V is the volume of test spesimens, in m^3[30].

3.2.6 Determination of swelling

Determining the swelling of fiberboards are done according to EN 317:2000 Particleboards and fibreboards - Determination of swelling in thickness after immersion in water. Swelling in thickness is determined by measuring the increase in thickness of the specimen after complete immersion in water.

For this experiment 4 specimens made by dry method and 4 specimens made by wet method were used. The specimens were square with the side length of (50±1) mm. For determining swelling the sample thicknesses were measured with caliper (d = 0,01 mm). Then the specimens were placed in water vertically keeping upper edge 20 mm under water. Samples were kept in water under the load at room temperature for 24 h. After that the sample thicknesses were measured again. Specimens before and after soaking are seen in Figures 23 and 24. Swelling was calculated after following formula:

$$\Delta s = \frac{s_2 - s_1}{s_1} \cdot 100\%$$

where

s_1 is thickness before soaking, mm;

s_2 is thickness after soaking, mm.

Water absorption was calculated after following equation:

$$\Delta w = \frac{m_2 - m_1}{m_1} \cdot 100\%$$

where

m_1 is the initial mass of sample, g;

m_2 is the mass after soaking, g [31].

Figure 23. Specimen before immersion in water

Figure 24. Specimens after immersion in water

3.2.7 Determination of resistance to axial withdrawal of screws

Determination of resistance to axial withdrawal of screws was done according to EN 320:2011 Particleboards and fibreboards – Determination of resistance to axial withdrawal of screws. Face withdrawal of screws is determined by measuring the force required to withdraw a defined screw from the specimen.

First the samples were cut out from hemp fiberboards according to standard EN 326-1. Five specimens were taken from each sample board. The specimens were rectangular with measurements (65x50 mm). Then the screws were inserted with screwdriver perpendicular to the surface of the test piece, located at the midpoints of one face as seen in Figure 25. For this test, a steel screw with size 4,2 mm x 45 mm were used. The screws were inserted into the test pieces in such a way, that (15±0,5) mm of complete thread was embedded in the specimen. For testing face screw holding on specimen with thickness of < 15 mm, the screw should be inserted in such a way that the length of the incomplete thread protrudes on the opposite side of the specimen.

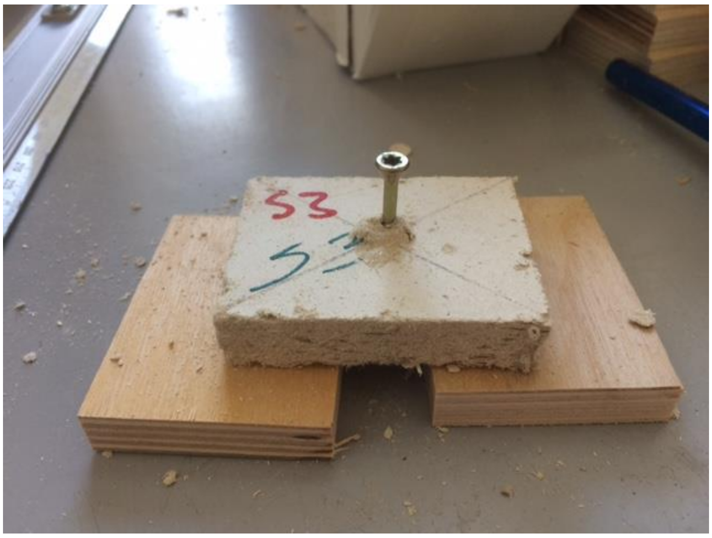

Figure 25. Location of screw

The specimens were mounted in the testing machine Instron 5866 so that the surface under test was not supported at any point closer than 15 mm to the periphery of the embedded part of the screw, and was held perpendicular to the direction of the force applied to the screw as seen in Figure 26. For the testing of face screw withdrawal on boards less than 15 mm thickness, the metal jig should be used. In this case the screw was inserted into the boring in the centre of the metal jig and the specimen was well restrained by the metal jig.

Figure 26. Test specimen mounting position

Machine applied an increasing axial force to the underside of the head of each screw in turn, through a stirrup incorporating a parallel-sided slot of suitable width to fit easily to the shank of the screw. The axial load was applied to the underside of the screw head at a constant rate of movement of (10±1) mm/min until maximum load was achieved. The maximum load was recorded to the nearest of 10 N sustained by the specimen during the withdrawal test on the face [32].

3.2.8 Determination of tensile strength

Determination of tensile strength is done according to standard EN 319:2000 Particleboards and fiberboards – Determination of tensile strength perpendicular to the plane of the board. Principle of this test is to determine the resistance to tension perpendicular to the surface of the specimen by submitting the latter to a uniformly distributed tensile force until rupture occurs. Tensile strength perpendicular to the plane of the board is determined by the maximum load in relation to the surface area of the test piece.

For this experiment 5 specimens made by dry method and 5 made by wet method were used. Test specimens were square with a side length of (50±1) mm. Before conducting the experiment the 20 wooden blocks (65x50 mm) compatible with the fixing device were glued to specimens using PVA glue (Penosil EN 2014/D3 Water resistant). Excess glue pressed out from the glue-line was removed. The specimens with glued on blocks were put under the load and left to cure for at least 24 h.

For current experiment testing machine Instron 5866 were used. First the testing assembly was placed in the grips and a force was applied until rupture occurred. The load was applied at a constant rate of crosshead-movement throughout the test. The rate of loading was adjusted so that the maximum load was reached within (60±30) s. Test was performed in tensile tester at speed of 20 mm/min, where the maximum load sustained by the test piece with a precision of 1% was recorded. The results from any test piece that exhibit partial or total glue-line failure or failure in the testing block were rejected. Tensile strength is expressed in N/mm^2 and calculated after following equation:

$$\sigma_t = \frac{P}{bl}$$

where

P is the force, N;

b is length of shear plane, mm;

l is width of shear plane, mm [33].

3.2.9 Determination of bending strength

Determination of bending strength is done according to standard EN 310:2002 Wood-based panels – Determination of modulus of elasticity in bending and bending strength. The modulus elasticity in bending and the bending strength are determined by applying a load to the center of a specimen supported at two points.

For this test 5 specimens of each sample board were used. Samples were rectangular with the dimensions of 50x150 mm. The measuring of the width and thickness of each specimen were done according to EN 325 at the following points:

- the thickness at the intersection of the diagonals;
- the width at the mid-length.

For this experiment testing machine Instron 5866 were used. First the test specimen was placed flat on the supports, with its longitudinal axis at right angles to those of the supports with the center point under the load. The load was applied at a constant rate of crosshead movement throughout the test. The rate of loading was adjusted so that the maximum load was reached within (60±30) s.

The deflection in the middle of the specimen was measured to an accuracy of 0,1 mm and this value was plotted against the corresponding loads measured to an accuracy of 1 % of the measured value. The maximum load was recorded to an accuracy of 1 % of the measured value. Tests were carried out on two groups of specimens according to the two directions of the board. Within each group half of the specimens were tested with the top face upwards and half with the bottom face upwards. The modulus of elasticity in N/mm^2 was calculated by following equation:

$$E_m = \frac{l_1^3(F_2 - F_1)}{4bt^2(a_2 - a_1)}$$

where

l_1 is the distance between the centres of the supports, mm;

b is the width of the test piece, mm;

t is the thickness of the test piece, mm;

$F_2 - F_1$ is the increment of load on the straight line portion of the load-deflection curve, N;

$a_2 - a_1$ is the increment of deflection at the mid-length of the test piece.

The bending strength in N/mm^2 was calculated by following formula:

$$f_m = \frac{3F_{max}l_1}{2bt^2}$$

where

F_{max} is the maximum load, N;

l_1 is the distance between the centres of the supports, mm;

b is the width of the test piece, mm;

t is the thickness of the test piece, mm [34].

3.2.10 Determination of air permeability

Determination of air permeability is done according to EN 12114:2000 Thermal performance of buildings – Air permeability of building components and building elements – Laboratory test method. Air permeability is air flow rate at reference conditions as a function of the pressure difference.

Test apparatus included the following:

- A rig into which the specimen can be fitted
- Means of applying a controlled air pressure difference over the specimen
- Means of producing rapid changes of air pressure differences, controlled within defined limits
- An apparatus for measuring the air flow rate to an accuracy of ± 5 %
- A means for measuring the applied air pressure difference to an accuracy of ± 5 %
- Means of sealing all joints of the test specimen.

For this experiment one specimen with measurements 100x100 mm of each sample board were used. First the test specimen was placed into the rig and tighten with screws by drilling as seen in Figure 27. Then the maximum pressure difference was selected. When available, the test pressure differences should be taken from the appropriate product specification. In this case no specification was available, so then the maximum pressure difference was selected according to the characteristics and future use of the specimen tested and to the purpose of the test. The minimum pressure difference should be at least equal to the smallest pressure difference measurable with the required accuracy of 5 % as it was in this case.

Altogether the procedure was dependent on the air-tightness of the test rig itself. A test rig was considered airtight because its residual air flow rate is less than 5 % of the smallest flow rate to be measured.

During the experiment three pressure pulses was applied with pressure regulator (Huba Control) as seen in Figure 28. Each pulse was maintained for at least three seconds. Each time a maximum pressure 550 Pa was applied and the data seen on air permeability display (SMC) was recorded. Each time, after the maximum pressure was applied, the pressure was lowered to zero before continuing with next pulse. If the results were zero, then the tested material was airtight and no following measurements were needed. Although when there was available data recorded during these three pressure pulses at maximum pressure, then another experiment was done also.

Figure 27. Fixing specimen into the rig

Before this another experiment the pressure steps were distributed in a geometric series between and including minimum and maximum pressure differences in such way that there were at least seven measured points. The full range was divided into N ($N \geq 6$) pressure steps, Δp_i, with equal intervals on a following logarithmic scale:

$$\Delta p_i = 10^{i\frac{log\Delta p_{max} - log\Delta p_{min}}{N} + log\Delta p_{min}}$$

where

Δp_{min} is minimum pressure difference, Pa;

Δp_{max} is maximum pressure difference, Pa;

i is pressure step;

N is number of different pressure steps.

Finally seven different pressure points were applied and the data was recorded [35].

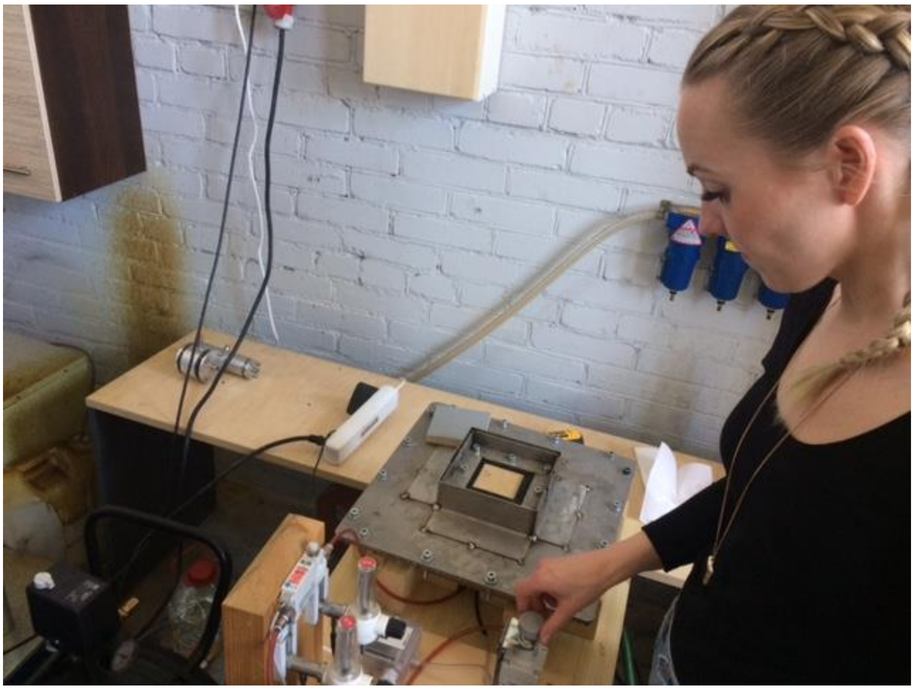

Figure 28. Applying pressure with pressure regulator

4 Results and discussion

4.1 Density

Data and results of test specimens densities are given in Table 11. Density of fiberboards are shown in Table 12. From the results and Figure 29 it can be concluded that the fiberboards made by dry method are denser than fiberboards made by wet method.

According to EWPAA product properties standard MDF density with thickness of 13-22 mm is 725 kg/cm^3. In this experimental work the average density of fiberboard made by dry method is 544 kg/cm^3. Therefore wood based MDF is denser than hemp fiberboard with 25 % difference. The cause of it can be the applied volume of pressure load during hot-pressing [36].

According to Pavatex product properties softboard density is 230 kg/cm^3. In current experiment the fiberboard average density made by wet method is 185 kg/cm^3. Therefore wood based softboard is about 20 % denser than hemp fiberboard. The differences may have occurred because of the different particle size and bonding abilities [16, 37].

Table 11 Density of test specimens

Sample		**Width, mm**	**Lenght, mm**	**Thickness in the middle, mm**	**Mass, g**	**Volume, m3**	**Density, kg/m^3**
Dry method fiberboard	1	49,86	49,34	15,07	19,52	0,000037	526,52
	2	49,99	50,01	14,55	19,56	0,000036	537,73
	3	49,94	49,90	14,72	20,00	0,000037	545,22
	4	49,91	49,77	14,80	20,87	0,000037	567,68
Wet method fiberboard	1	48,93	49,53	22,49	10,11	0,000055	185,49
	2	49,49	49,60	22,74	10,69	0,000056	191,51
	3	49,46	49,56	22,48	9,93	0,000055	180,21
	4	49,73	49,55	22,72	10,29	0,000056	183,80

Table 12 Density of fibreboards

Board	**Density of test specimens, kg/m^3**				**Average density of board, kg/m^3**	**Standard deviation**
	1	**2**	**3**	**4**		
Dry method fiberboard	526,52	537,73	545,22	567,68	544,29	17,39
Wet method fiberboard	185,49	191,51	180,21	183,80	185,25	4,72

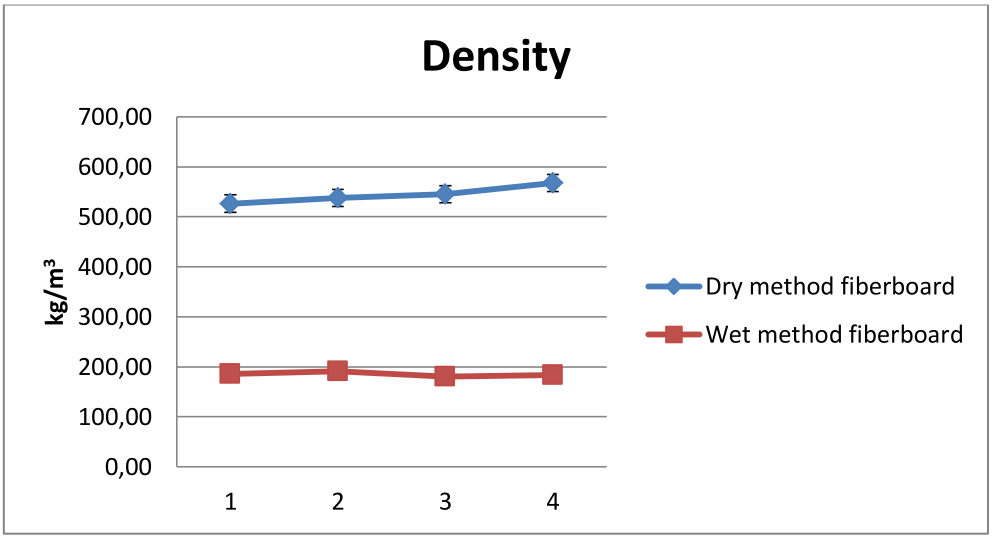

Figure 29. Density of various hemp fiberboards

4.2 Swelling

Data and results of test specimens swelling properties and water absorption are given in Table 13. Unfortunately samples made by dry method dissolved in water and no measureable entity were left as seen in Figure 30. The average swelling of hemp fiberboard made by wet method is 8,97 % and the average water absorption is 480,11 % as seen in Figures 31 and 32.

According to requirements given in EN 622-4 the swelling in thickness of wood based fiberboard made by wet method is 10 % for boards with >19 mm thickness. In this experimental work the average swelling for hemp fiberboard made by wet method is about 9

%. The difference is 10 % because of the wood and hemp fibre morphology differences [16, 38].

According to standard EN 622-5 the swelling is 12 % for dry method fiberboards with thickness 12-19 mm. Also EWPAA product properties show that the wood based MDF swelling is approximately 8-12 %. Unfortunately in current experimental work no data was recorded of swelling properties of hemp fiberboard made by dry method due to dissolved specimens [36, 39].

Table 13 Swelling of hemp fiberboard

Sample		**Thickness before soaking, mm**	**Thickness after soaking, mm**	**Mass before soaking, g**	**Mass after soaking, g**	**Swelling, %**	**Water absorption, %**
Dry method	1	15,07	-	19,52	-	-	-
	2	14,55	-	19,56	-	-	-
	3	14,72	-	20	-	-	-
	4	14,8	-	20,87	-	-	-
Wet method	1	22,49	24,5	10,11	59,07	8,94	484,27
	2	22,74	24,87	10,69	60,86	9,37	469,32
	3	22,48	24,34	9,93	57,88	8,27	482,88
	4	22,72	24,83	10,29	60,09	9,29	483,97
					Average	8,97	480,11
					Standard deviation	0,50	7,22

Figure 30. Hemp fiberboard made by dry method after soaking

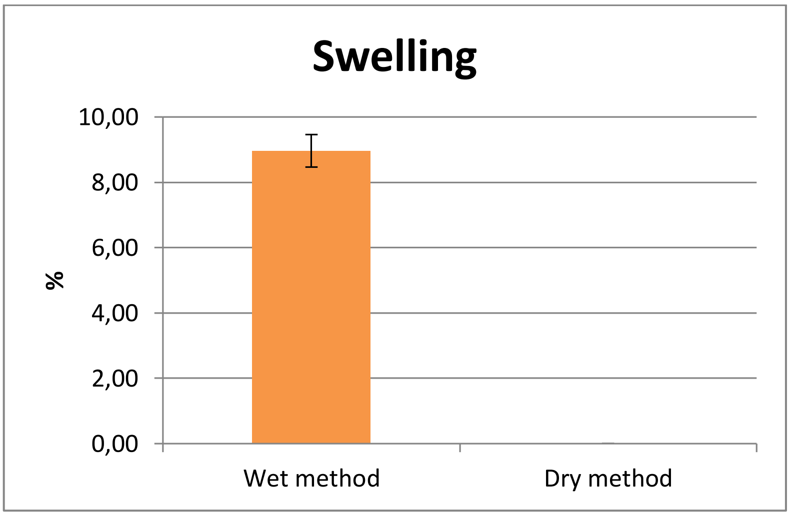

Figure 31. Average swelling

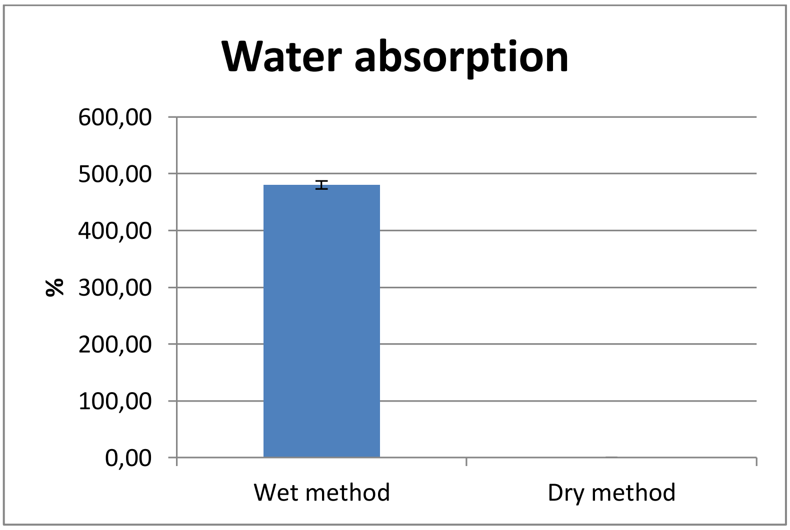

Figure 32. Average water absorption

4.3 Resistance to axial withdrawal of screws

Results and data of resistance to axial withdrawal of screws are shown in the Table 14 and the diagrams recorded by test machine are depicted in Annex 2. The comparison of average resistances are seen in Figure 33, where it can be concluded that specimens covered with paper using PVA glue were the most resistant ones and specimens made by wet method were least resistant to axial withdrawal of screws. The material made by wet method was even so weak, that three out of five specimens broke during the test as seen in Figure 34.

According to standard 622-4 the resistance to axial withdrawal of wood based fiberboards made by dry method is 30 N/mm. In addition the EWPAA produced MDF (thickness of 13-22 mm) resistance to axial withdrawal is 47 N/mm. The results of current experiment show that the average resistance to withdrawal of hemp fiberboards is 12 N/mm. Therefore the wood based fiberboard is more resistant to axial withdrawal than hemp board. Difference is 60-74 % [36, 40].

According to EcoBoards product properties the resistance to axial withdrawal of wood based softboards is 58 N/mm. In this case the average result of hemp fiberboard made by wet method is 2 N/mm. Differences is about 96 %. This huge difference may have occurred because wood contains more lignin and therefore is stronger. The reason may be also the breaking of specimens during the test – only two more or less adequate results were gained [16, 41].

Table 14 Resistance to axial withdrawal of screws

Sample		**Thickness, mm**	**Maximum load, N**	**Resistance to axial withdrawal, N/mm**	**Average, N/mm**	**Standard deviation**
Dry	1	15,16	180,7	11,92	12,09	1,93
	2	15,17	136,22	8,98		
	3	14,58	205,33	14,08		
	4	15,4	189,38	12,30		
	5	14,96	197,16	13,18		
UF	1	14,13	329,21	23,30	20,07	10,31
	2	13,04	468,76	35,95		
	3	16,24	283,73	17,47		
	4	15,83	138,19	8,73		
	5	12,79	190,32	14,88		
PVA	1	15,4	493,65	32,06	26,65	4,18
	2	15,86	369,86	23,32		
	3	15,22	369,07	24,25		
	4	14,42	436,27	30,25		
	5	14,52	339,53	23,38		
Wet	1	22,66	47,19	2,08	2,23	0,20
	2	22,33	52,95	2,37		

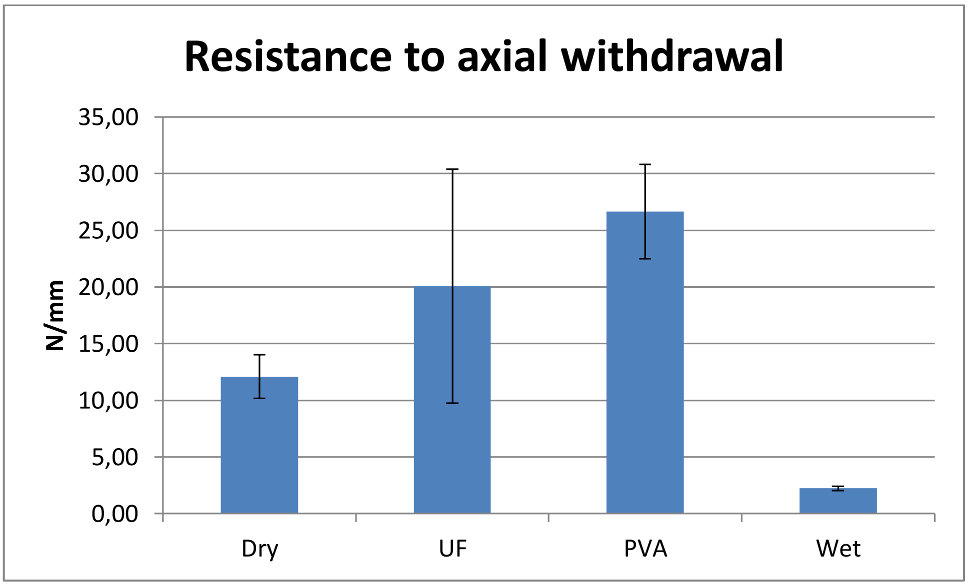

Figure 33. The average resistance to axial withdrawal for various fibreboards

Figure 34. Sample made by wet method broke during the test

4.4 Tensile strength

Results and data of tensile strength perpendicular to the plane of the board are shown in the Table 15 and the diagrams recorded by test machine are depicted in Annex 3. Average tensile strength of fiberboard made by dry method is 0,0147 N/mm^2 and tensile strength of fiberboard made by wet method is 0,0068 N/mm^2. Unfortunately three out of five specimens made by wet method broke loose from the wooden blocks before the experiment, therefore there may not be enough data for adequate results. Although from the available data and as seen in Figure 35 it can be concluded that the fibreboards made by dry method are stronger.

According to standard 622-5 the tensile strength of wood based fiberboard with 12-19 mm thickness is 0,55 N/mm^2. Also the EWPAA produced MDF with thickness of 13-22 mm tensile strength is 0,75 N/mm^2. In this experimental work the average tensile strength of hemp fiberboard made by dry method is 0,015 N/mm^2. The differences are about 96-98 % [36, 39].

According to Pavatex produced softboard the wood based board tensile strength is 0,015 N/mm^2. In current experiment the tensile strength of hemp fiberboard made by wet method is 0,007 N/mm^2. The difference is about 54 % because wood contains more lignin than hemp and therefore wood based fiberboards are bonded better and also stronger [16, 37].

Table 15 Tensile strength of fiberboards

Sample	**Dry method**		**Wet method**	
	Maximum load, N	**Tensile strength, N/mm^2**	**Maximum load, N**	**Tensile strength, N/mm^2**
1	36,71	0,0147	21,32	0,0085
2	37,02	0,0148	12,53	0,005
3	32,16	0,0129	-	-
4	29,56	0,0118	-	-
5	48,71	0,0195	-	-
Average		0,0147	Average	0,0068
Standard deviation		0,0029	Standard deviation	0,0025

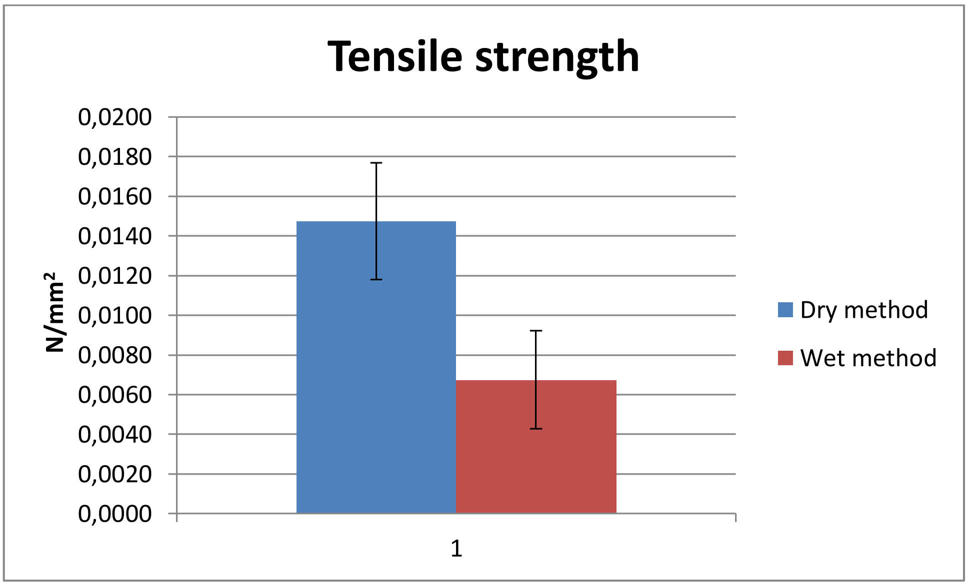

Figure 35. Tensile strength perpendicular to the plane

4.5 Bending strength

Results and data of bending strength of various fibreboards are shown in the Tables 16 to 19 and the diagrams recorded by test machine are depicted in Annex 1. Average bending strength of different boards are seen in Figure 36, where it can be concluded that the strongest material was fibreboard made by dry method and covered with paper using UF resin and the weakest was fibreboard made by wet method. Same conclusions can be made of modulus of elasticity results, which are seen in Figure 37.

According to standard 622-4 the bending strength requirements for wood based soft boards with thickness over 19 mm are 0,8 MPa. In this experimental work the average bending strength for soft board was 0,31 MPa. Therefore hemp soft board is weaker. Difference is 61,25 % because wood contains more lignin than hemp and therefore the fibers are bonded better [16, 38].

According to standard 622-3 the bending strength for wood based fiberboard made by dry method with thickness over 10 mm is 8 MPa. In current experimental work the average bending strength of hemp fiberboards made by dry method is about 1 MPa. From previous it can be concluded that hemp fiberboard is weaker. The difference is about 87 % [40].

Table 16 Bending strength of fiberboard made by dry method

Sample	Thickness, mm	Maximum compressive load, N	Compressive extension, mm	Modulus of elasticity, MPa	Bending strength, MPa
1	15,6	62,36	1,4	89,85	0,77
2	15,6	80,08	1,26	117,55	0,99
3	14,5	51,72	2,02	103,24	0,74
4	15,4	46,01	1,86	74,34	0,58
5	15,4	59,7	2,05	85,28	0,76
			Average	94,05	0,77
			Standard deviation	16,73	0,15

Table 17 Bending strength of fiberboard made by dry method (UF)

Sample	Thickness, mm	Maximum compressive load, N	Compressive extension, mm	Modulus of elasticity, MPa	Bending strength, MPa
1	14,1	274,24	1,9	528,03	4,14
2	14,5	210,1	1,6	436,84	3
3	14,6	276,7	1,66	503,82	3,89
4	14,6	170,24	1,28	360,96	2,4
5	14,7	206,4	1,85	326,68	2,87
			Average	431,27	3,26
			Standard deviation	87,38	0,73

Table 18 Bending strength of fiberboard made by dry method (PVA)

Sample	Thickness, mm	Maximum compressive load, N	Compressive extension, mm	Modulus of elasticity, MPa	Bending strength, MPa
1	15,2	147,72	1,88	218,41	1,92
2	14,9	234	2,39	328,19	3,16
3	15,5	127,42	1,48	172,94	1,59
4	15,5	140,99	1,61	212,26	1,76
5	15,5	186,65	1,58	207,95	2,33
			Average	227,95	2,15
			Standard deviation	58,76	0,63

Table 19 Bending strength of fiberboard made by wet method

Sample	Thickness, mm	Maximum compressive load, N	Compressive extension, mm	Modulus of elasticity, MPa	Bending strength, MPa
1	21,9	52,49	2,7	15,34	0,33
2	21,3	50,35	3,18	12,96	0,33
3	22,5	48,55	2,16	11,69	0,29
4	21,7	51,18	2,84	15,15	0,33
5	22,8	49,49	2,21	11,78	0,29
			Average	13,38	0,31
			Standard deviation	1,77	0,02

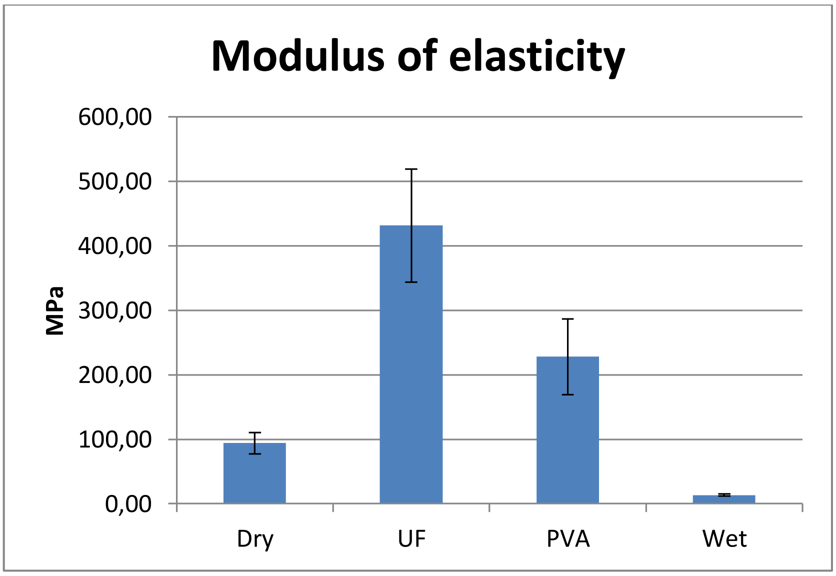

Figure 36. Modulus of elasticity of various fibreboards

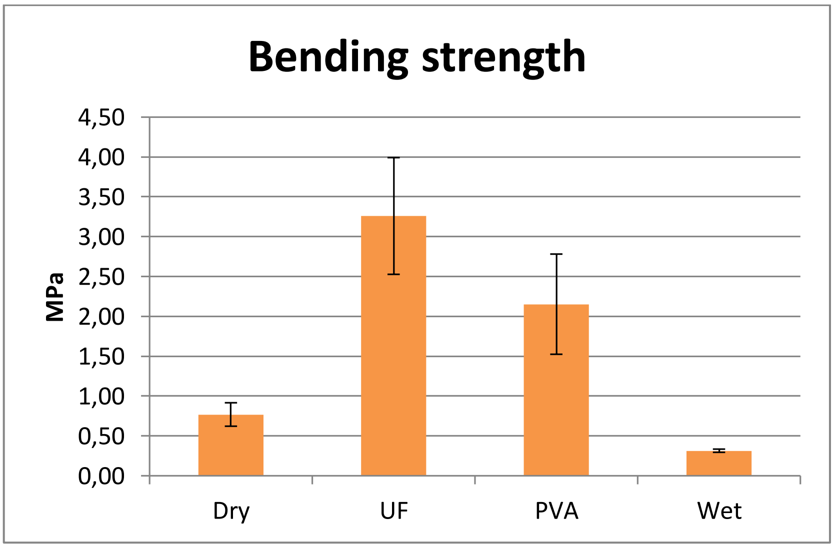

Figure 37. Bending strength of various fibreboards

4.6 Air permeability

Results and data of air permeability tests are seen in Tables 20 and 21. All the fiberboard samples made by dry method were airtight, therefore the given results only concern fiberboards made by wet method. In Figures 38 and 39 the air permeability results are compared with results of hemp and wood particleboards, which were made by bachelor student. From previous it can be concluded that hemp fiberboard is less airtight than hemp particleboard, although more airtight than board made out of wood particles. The reasons, why fiberboards made by dry method are more air tight than particleboards, may be that fiberboards are denser and less porous than particleboards.

Table 20 Air permeability of fiberboard made by wet method at 550 Pa

No	Pressure, Pa	Air permeability, L/min
1	550	1,85
2	550	1,85
3	550	1,85
Average		1,85
Standard deviation		0

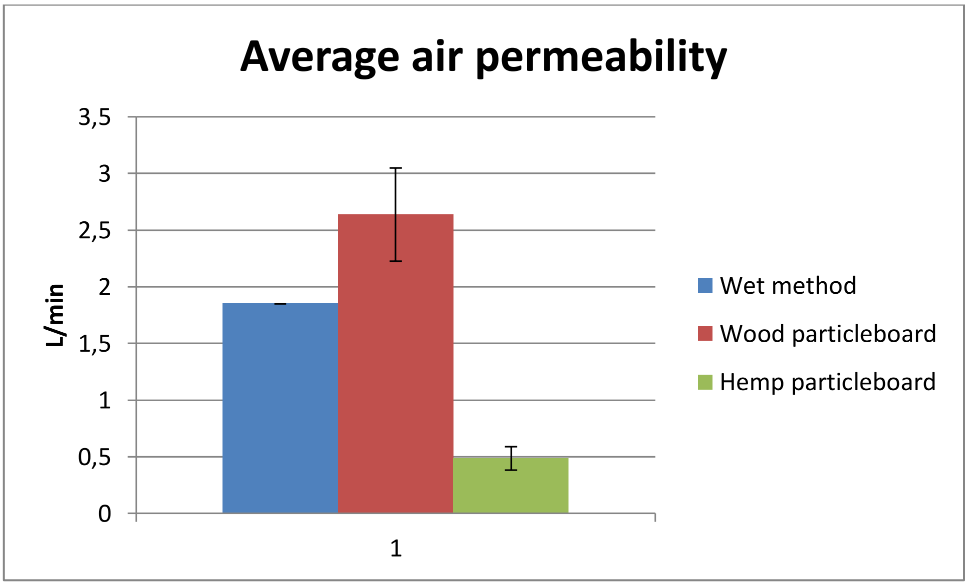

Figure 38. Average air permeability

Table 21 Air permeability of fiberboard made by wet method at different pressure steps

Pressure step	Pressure, Pa	Air permeability, L/min
0	50	0,2
1	73	0,27
2	108	0,4
3	158	0,57
4	232	0,83
5	341	1,19
6	500	1,7

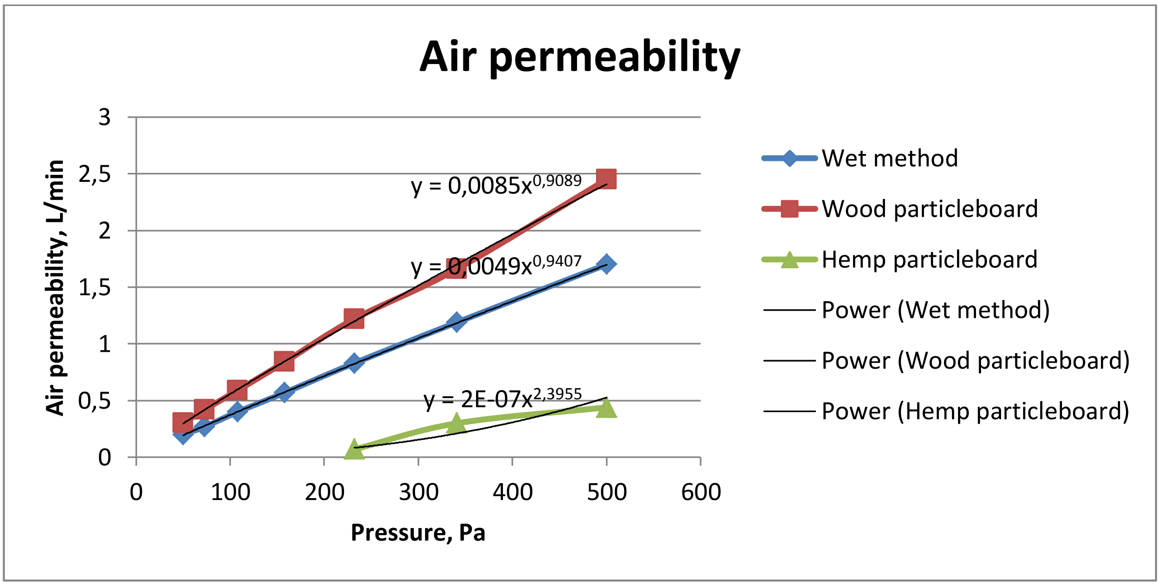

Figure 39. Air permeability

Conclusions

Fibre hemp is mainly a dioecious plant. Male and female plants are indistinguishable from each other before flowering. The male plants grow more quickly, which leads to uneven maturity at harvest. Industrial hemp can be cultivated on very different types of soils and it is considered to be one of the most sturdy and adaptable crops, which can be grown without using any pesticides. Industrial hemp varieties such as Kompolti and USO 31 are known for their high natural fibre content. Both of these cultivars are suitable for growing in continental climate zones. To acquire fiber from hemp plant and for producing hemp fibre insulation materials various pretreatments and process technologies shall be passed through. After harvesting the fibres must be separated from the rest of the plant. This separation has usually been achieved by retting following mechanical extraction processes. In the production chain of hemp fibre thermal insulations, the processing steps depend on the structure of the insulation produced. The insulation materials made from hemp are often completely biodegradable. They possess outstanding thermal insulation properties, though unfortunately hemp insulation is 2 to 4 times more expensive compared to glass or mineral wool.

The raw material for making hemp boards were acquired in a form of shives from company Hempson OÜ in Saaremaa, Estonia. For producing hemp fibreboards the hemp shives were grinded with separative milling by semiindustrial disintegrator DSL-115 to the average particle size of 0,136. Some fiberboards were made by dry method and others were made by wet method. Urea-formaldehyde resin and hardener were used as an adhesive for boards made by dry method. Boards made by wet method were bonded without using any binders. Some boards made by dry method were covered with kraft paper on the both sides using UF resin and PVA glue. Altogether six fiberboards were covered using PVA and nine of them were glued with urea-formaldehyde resin. Three covered fibreboards, which were glued with UF resin came out cracked. Cracking may have occured due to repeated contact with high temperature. Cracked fiberboards were not used during experiments.Various tests were carried out on produced fiberboards, including determination of density, swelling, resistance to axial withdrawal, tensile strength, bending strength and air permeability.

From the results it can be concluded that the fiberboards made by dry method are denser than fiberboards made by wet method. When it comes to swelling and water absorption results then unfortunately samples made by dry method dissolved in water and no measureable entity were left. Therefore no comparison of swelling and water absorption properties can be made between dry and wet method hemp fiberboards. In case of resistance to axial withdrawal the specimens covered with paper using PVA glue were the most resistant ones and specimens made by wet method were least resistant to axial withdrawal of screws. The material made by wet method was even so weak, that three out of five specimens broke during the test. About the results of tensile strength perpendicular to the plane of the board, unfortunately three out of five specimens made by wet method broke loose from the wooden blocks before the experiment, therefore there may not be enough data for adequate results. Although from the available data it can be concluded that the fibreboards made by dry method are stronger. From average bending strength of different boards it can be concluded that the strongest material was fibreboard made by dry method and covered with paper using UF resin and the weakest was fibreboard made by wet method. When it comes to results of air permeability tests, then all the fiberboard samples made by dry method were airtight. The air permeability results of wet method hemp fiberboards were compared with results of hemp and wood particleboards, which were made by bachelor student. From these results it can be concluded that hemp fiberboard is less airtight than hemp particleboard, although more airtight than board made out of wood particles.

Abstract

In recent years the field of thermal protection in buildings are focusing more upon ecological properties. Environmental awareness is now not only limited to energy savings but also contained within ecologically sound construction. That is the reason why natural raw materials such as hemp, flax and others are gaining more interest nowadays. Hemp insulation materials also have many great properties and are user-friendly while installing them.

The aim of this Master's thesis is to explore the industrial hemp based insulation materials. Also to figure out hemp fibre properties that are suitable for usage in insulation material, how to treat hemp fibres to make insulation material and how much hemp fibre is needed for making insulation material. This Master's thesis contains overview of hemp cultivation and the hemp plant in general following descriptions of some common cannabis varieties grown in Europe. In addition the pretreatments and process technology of hemp plant to hemp fibre insulation material are described. Also processes of manufacturing insulation material from hemp depending on the final product are demonstrated. Furthermore advantages and limitation of hemp fibre insulation products are listed. Next the directions and advice of how to install hemp insulation materials are given and suitable application areas are referred. Finally materials and methods of making hemp fiberboard in various methods are described and results of these readymade fiberboard properties are presented.

The raw material for making hemp boards were acquired in a form of shives from company Hempson OÜ in Saaremaa, Estonia. For producing hemp fibreboards the hemp shives were grinded with separative milling by semiindustrial disintegrator DSL-115 to the average particle size of 0,136. Urea-formaldehyde resin (Achema KF-FE) and hardener (Casco 2535) were used as an adhesive for boards made by dry method. Boards made by wet method were bonded without using any binders. Some boards made by dry method were covered with kraft paper on the both sides using UF resin and PVA (Penosil EN 2014/D3 Water resistant). Various tests were carried out on produced fiberboards, including determination of density, swelling, resistance to axial withdrawal, tensile strength, bending strength and air permeability.

From the results it can be concluded that the fiberboards made by dry method are stronger and tougher than fiberboards made by wet method. Only shortcoming was their water resistance

as seen from swelling and water absorption results, where samples made by dry method dissolved in water.

Resümee

Viimastel aastatel on ehitusvaldkond muutunud väga keskkonna teadlikuks, mitte ainult energia säästmise koha pealt, kuid on rohkem hakatud kasutama ka loodussõbralikke materjale. See on ka põhjuseks miks naturaalsete toormaterjalide nagu näiteks kanepi ja lina vastu on tänapäeval huvi suurenenud. Kanepist toodetud isolatsioonimaterjalidel on palju suurepäraseid omadusi ja nad on paigladamisel väga kasutamissõbralikud.

Käesoleva magistritöö eesmärgiks oli uurida isolatsioonimaterjale, mis on valmistatud tööstuslikust kanepist. Lisaks tuli välja mõelda kuidas ja millega töödelda kanepi kiudu, et sellest saaks valmistada isolatsioonimaterjali ning palju kiudu on vaja ühe plaadi valmistamiseks. Käesolevas magistritöös on antud ülevaade tööstusliku kanepi taimest üldiselt ja selle kasvatamisest, millele järgneb kirjeldus mõndade levinud tööstusliku kanepi sortidest, mida kasvatatakse Euroopas. Lisaks on kirjeldatud kanepi taimest isolatsioonimaterjali saamise eeltöötluseid ja protsessi tehnoloogiad. Veel on selgitatud isolatsioonimaterjali tootmise protsesse sõltuvalt valmistoodetest ning loetletud kanepi isolatsioonimaterjali eeliseid ja piiranguid. Järgmisena on välja toodud juhised ja nõuanded, kuidas ja kuhu tuleks paigaldada kanepist valmistatud isolatsioonmaterjale. Viimasena on kirjeldatud materjalid ja meetodid kanepijahust kiudplaadi valmistamisest erinevatel meetoditel ning esitletud nende valmis plaatide omadused.

Kanepi isolatsiooniplaatide valmistamise toormaterjaliks oli kanepiluu, mida saadi Saaremaal asuvast ettevõttest Hempson OÜ. Kiudplaadi valmistamiseks oli vaja kanepiluu eelnevalt jahvatada. Jahvatatud kanepikiu keskmiseks suuruseks oli 0,136 mm. Kuivmeetodiga plaatide valmistamiseks kasutati sideainena ureaformaldehüüd vaiku (Achema KF-FE) segatuna kõvendiga (Casco 2535). Märgmeetodiga plaatide valmistamisel sideainet ei kasutatud. Mõned kuimeetodil tehtud plaadid kaeti mõlemalt poolt jõupaberiga. Selleks kasutati kas ureformaldehüüd vaiku või veekindlat PVA liimi (Penosil EN 2014/D3). Toodetud kiudplaatide peal viidi läbi erinevaid katseid nagu näiteks tiheduse, pundumise, tõmbetugevuse, paindetugevuse ja õhuläbilaskvuse määramine.

Katsete tulemustest võib järeldada, et kuivmeetodil valmistatud kiudplaadid on tugevamad ja vastupidavamad kui märgmeetodil valmistatud kiudplaadid. Ainuke puudujääk kuivmeetodil

valmistatud plaatidel oli halb veekindlus, mis tuli välja pundumise katsest, kus kuivmeetodil valmistatud katsekeha lagunes vees ära.

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Annex 1

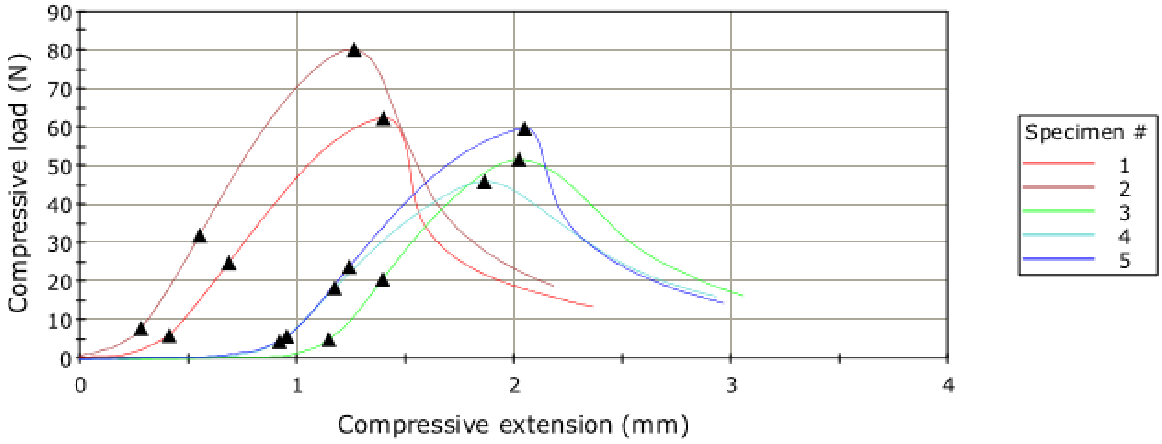

Figure 40. Bending strength diagram of hemp fiberboard made by dry method

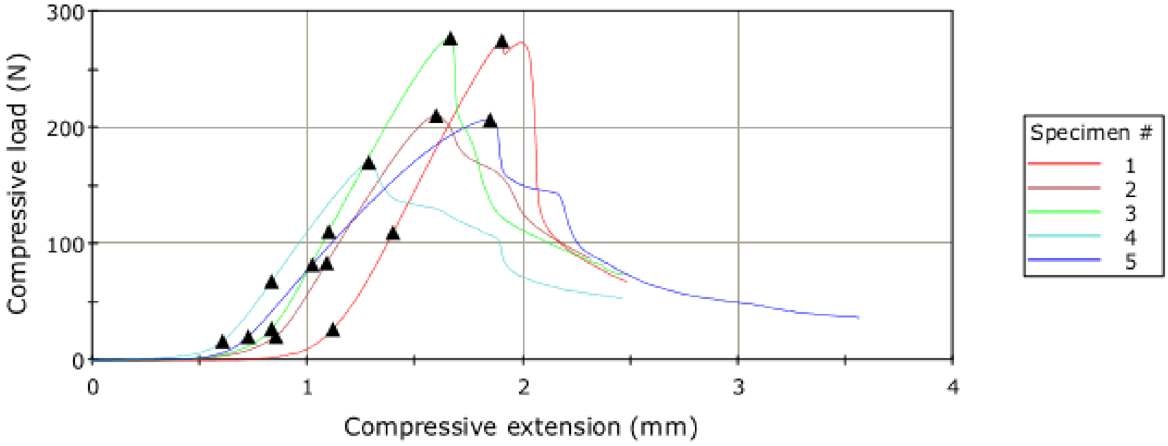

Figure 41. Bending strength diagram of hemp fiberboard made by dry method covered using UF resin

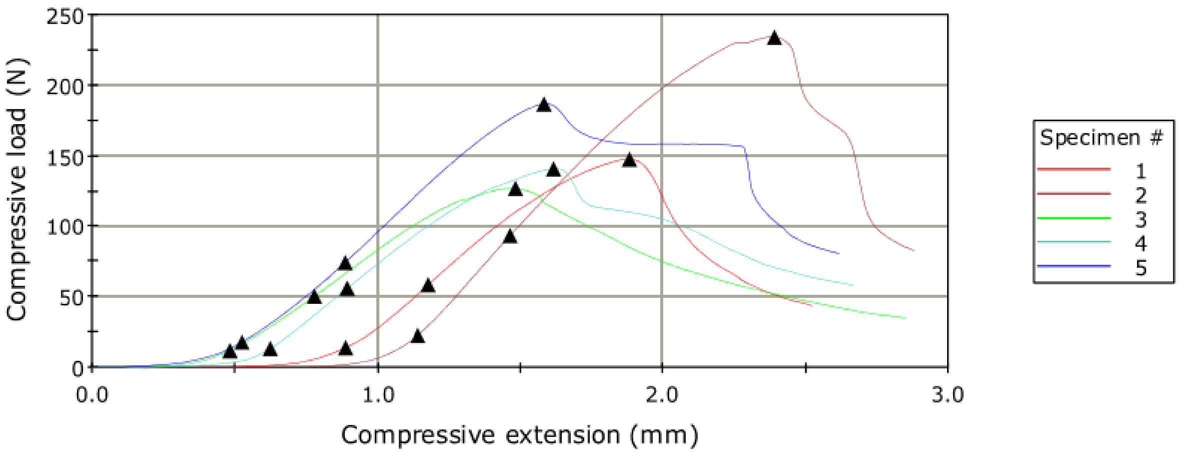

Figure 42. Bending strength diagram of hemp fiberboard made by dry method covered using PVA glue

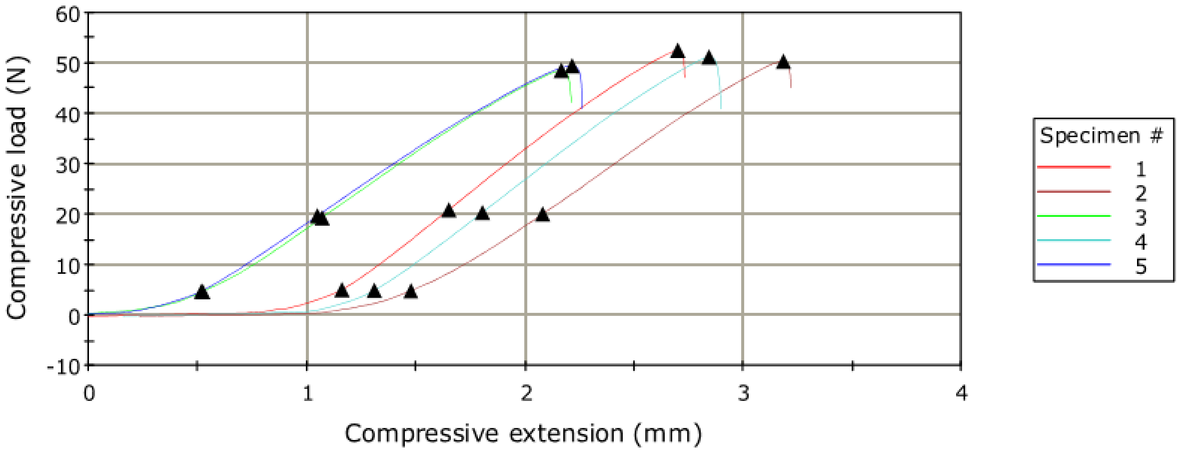

Figure 43. Bending strength diagram of hemp fiberboard made by wet method

Annex 2

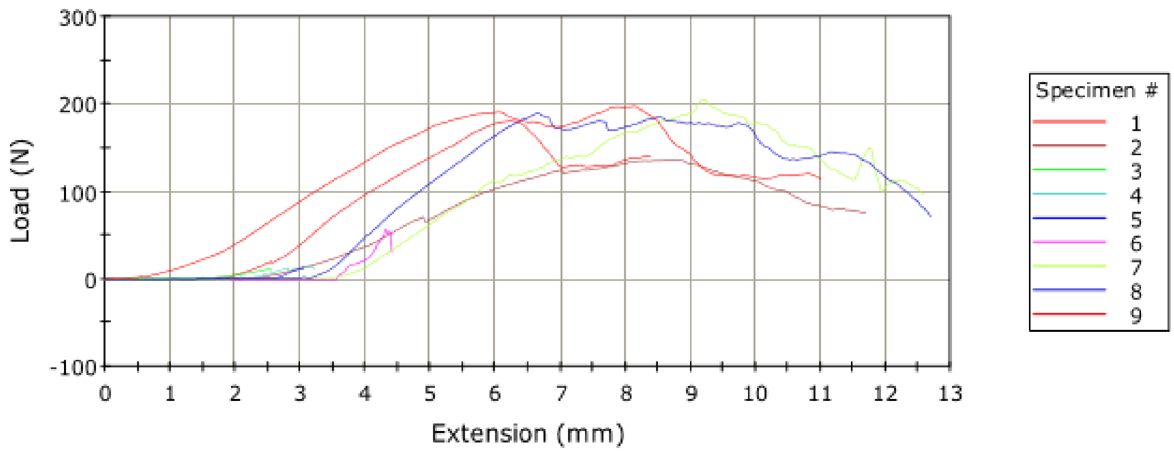

Figure 44. Resistance to axial withdrawal diagram of hemp fiberboard made by dry method

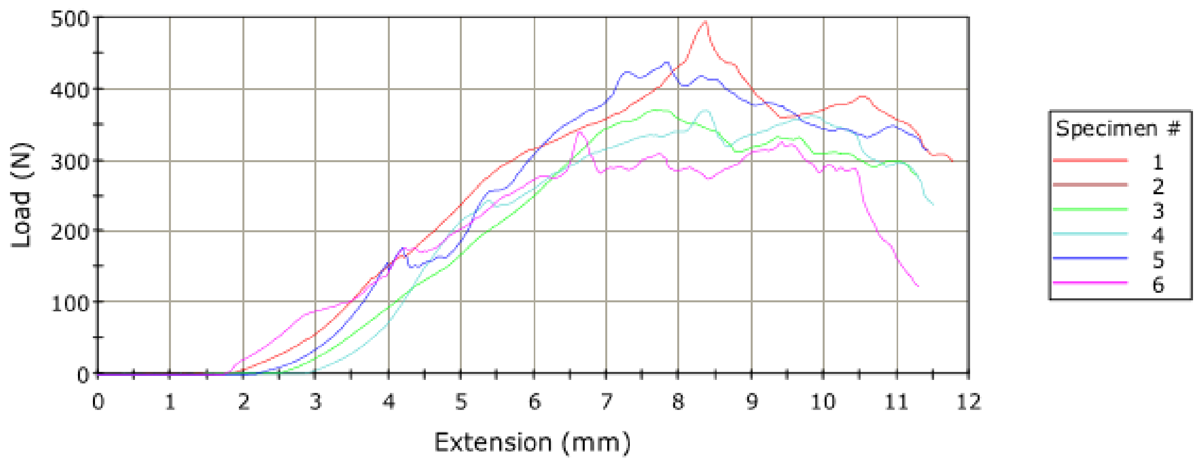

Figure 45. Resistance to axial withdrawal diagram of hemp fiberboard made by dry method covered using PVA

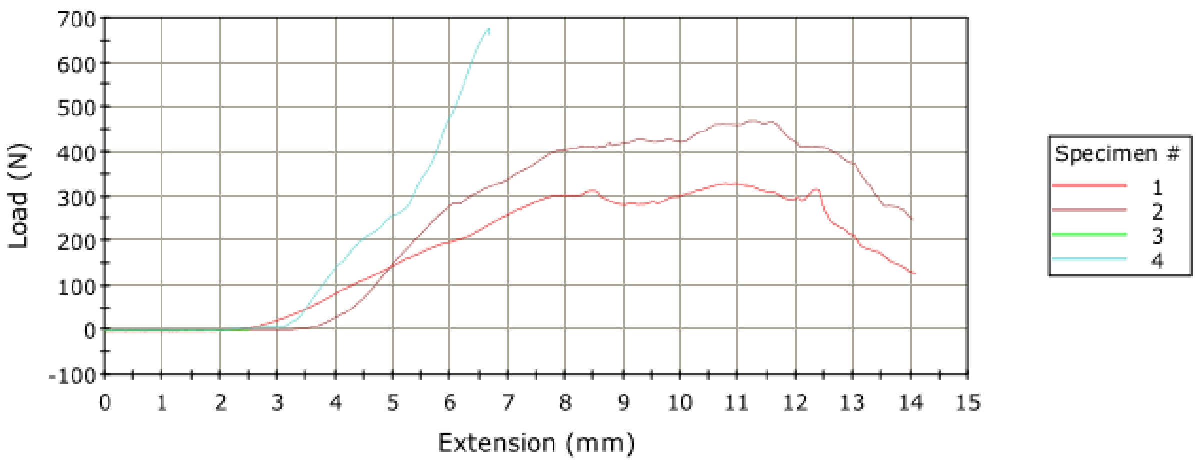

Figure 46. . Resistance to axial withdrawal diagram of hemp fiberboard made by dry method covered using UF (1)

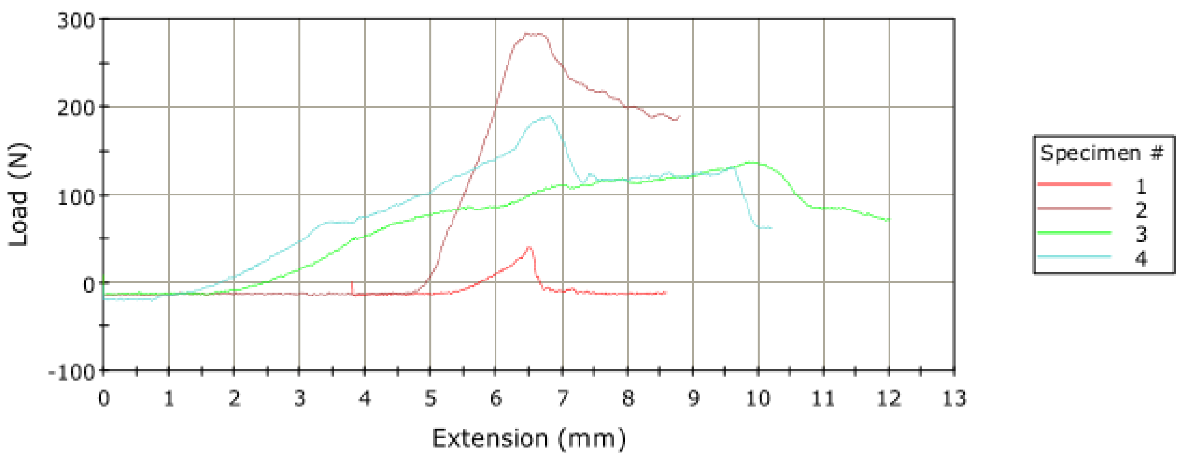

Figure 47. Resistance to axial withdrawal diagram of hemp fiberboard made by dry method covered using UF (2)

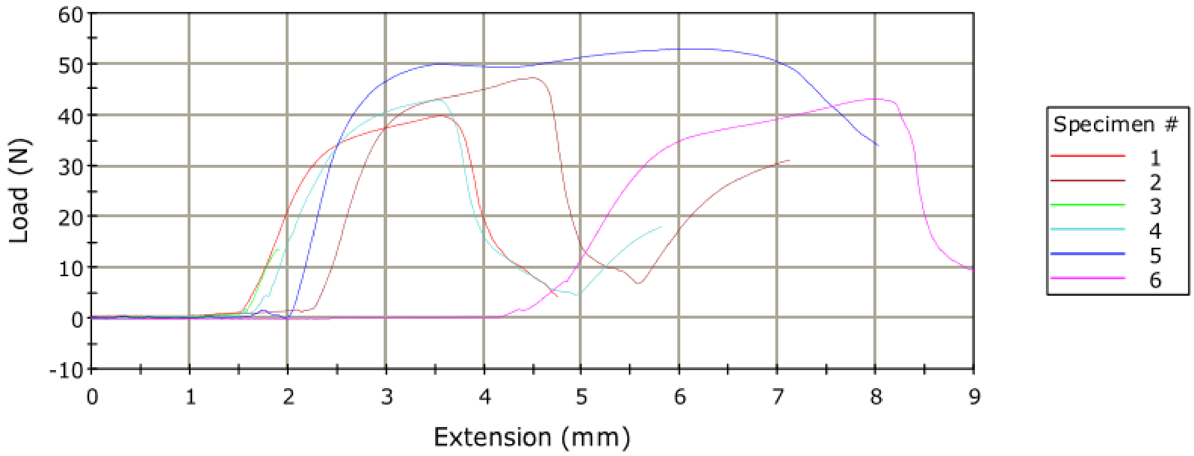

Figure 48. Resistance to axial withdrawal diagram of hemp fiberboard made by wet method

Annex 3

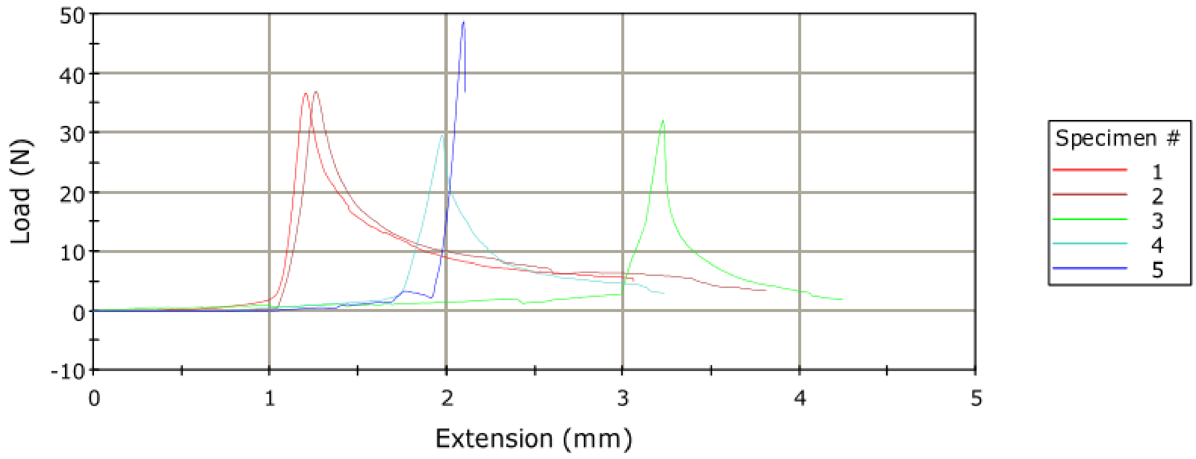

Figure 49. Tensile strength diagram of hemp fiberboard made by dry method

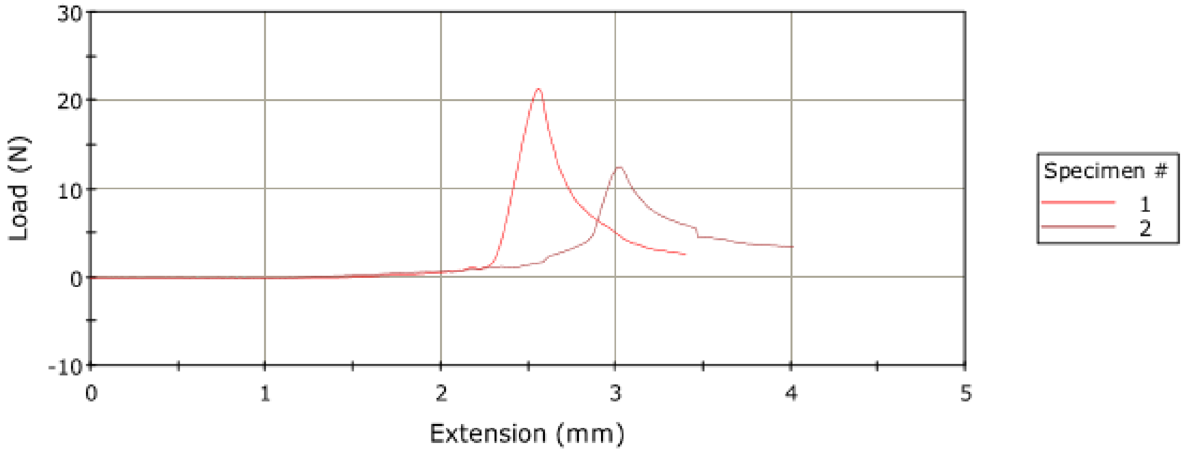

Figure 50. Tensile strength diagram of hemp fiberboard made by wet method