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Fire and Mechanical Properties of Hemp and Clay Boards for Timber Structures

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Abstract. The use of timber with other bio-based building materials is often restricted due to the fire hazard. The primary protection for timber against fire is provided by cladding. Currently, there is limited fire protection design data on clay and hemp boards since they are relatively new products. Furthermore, the mechanical performance of boards is of utmost importance in timber frame assemblies. This paper presents a test program that determines the tensile and bending strength of boards accompanied by a comparison to widely used gypsum plasterboards. The fire protection effect for timber is assessed by using a cone heater. Main results indicate that clay and hemp boards are adequate alternatives for the gypsum plasterboards as they can demonstrate similar performance. Hemp boards made by dry method perform significantly better compared to the ones made by wet method. Clay boards with special additive demonstrate increased fire performance compared to more ecological boards. This study contributes to further research that is needed in order to provide design parameters for sustainable building solutions in the future.

1. Introduction

The quest for resource efficient building design has become a key driver of innovation in the construction sector. Natural building materials such as wood, hemp and clay have proven their quality and longevity in buildings that comply well with the contemporary requirements for a healthy and sustainable building environment.

However, the combustibility of timber is one of the main barriers that building regulations limit its use in buildings. In Europe, the fire design of timber structures is given in EN 1995-1-2 [1]. Currently, only a few building materials are determined as fire protection materials for timber, e. g. gypsum plasterboards. Also, the new fire technical guideline [2] does not provide any design data to determine the EI criteria for timber structures with hemp or clay boards.

The use of sustainable materials as fire protection could provide a major contribution towards carbon efficient buildings in the future. Bio-based building materials in this particular context embody several advantages [3] over other convectional materials. Today, limited data exist on the fire and mechanical properties of such building boards. Clay and hemp boards are relatively new products on the market as there is no product standard on the European level yet. In the near future, a product standard for clay boards is going to be published in Germany [4]. The fire classification of construction products and building elements is described in EN 13501-2 [5] and hardly any data exist on the performance of hemp and clay boards. Only a few available studies on fire protection ability of some clay boards exist [6].

However, there have been several studies when it is shown that hemp shives are used for making the shiveboards [7][8][9][10][11]. It is also shown that these hemp shive-based insulation materials have good thermal insulation, antiseptic and hydric regulation properties [12][13][14].

In this paper, the material properties with regards to the mechanical and fire performance are examined for a selected range of various boards. The fire protection ability is assessed by using a small-scale method since the larger scale fire tests are costly and time-consuming to carry out a basic investigation. A cone calorimeter (ISO 5660 [15]) is used that has proven its dependability to estimate similar results to the ones gained in the furnace tests for the basic protection time of a material and the start time of charring of timber [16][17]. The mechanical performance of the hemp and clay boards was evaluated by their tensile and bending strength and with screw withdrawal force.

2. Materials

2.1. Hemp shive boards and wood particleboards

The same procedure was used for making the hemp shive boards (Hemp S, see Table 1) and wood particleboards (Wood P, see Table 1). Hemp shive boards were made from the hemp shives that were obtained by the company Hempson OÜ. A wood particleboard was made from wood particles that were brought from AS Repo Vabrikud. For making the 220x220 mm board, the 340g of hemp shives or wood chips (7 % moisture content) were taken and mixed with adhesive in the mixer. For an adhesive, a urea-formaldehyde resin Achema KF-FE and hardener Casco 2535 were used. The urea-formaldehyde resin was taken 11 wt% of the hemp shives or wood particles dry matter and hardener was added to the resin in the amount of 10 wt% of the resin. The adhesive and hemp shives or wood chips were mixed in the laboratory mixer for 3 minutes, where the adhesive was added slowly to the hemp shives/wood chips during the mixing. The hemp shives or wood chips mixed with adhesives were placed into the mat-forming frame and thickened with a hand press. The board thickness was adjusted with the thickness calibrators, which were placed on the edges of the board. The pressing plate was added on the top of the formed mat and then the mat was added into a hot press for 5 min at 110 °C at a pressure of 1.2 MPa.

2.2. Hemp fibreboards

2.2.1. Dry method fibreboards. Hemp fibreboards (Hemp F, see Table 1) were made with hemp bast fibres that were ground to smaller particle size of 0.136 mm and then mixed with urea-formaldehyde resin Achema KF-FE in the amount of 11 wt% of the hemp fibres dry matter and hardener Casco 2535 was added to the resin in the amount of 10 wt% of the resin. Next step was mixing the hemp fibres with the adhesive in the laboratory mixer for 3 min. The hemp fibres mixed with adhesives were placed into the mat-forming frame and thickened with a hand press. The board thickness was adjusted with the thickness calibrators that were placed on the edges of the board. The pressing plate was added on the top of the formed mat and then the mat was added into a hot press for 5 min at 110 °C at a pressure of 1.2 MPa.

Half of the hemp fibreboards were covered with the kraft paper (Hemp FK, see Table 1). For glueing, the same adhesive was used for the board production and the boards were covered with the kraft paper on both sides. Then the kraft paper covered boards were set into the hot press at for 5 min at 110 °C at a pressure of 0.3 MPa.

2.2.2. Wet method fibreboards. Wet method hemp fibreboards (Hemp FW, see Table 1) were made of the same hemp bast fibres sizes as the dry method boards. For the one board, 150g of hemp fibres were taken with the dry matter content of 91 %. Fibres were mixed with water in a blender and then poured into the drainer cylinder of the sheet former. Then the mixed fibres were diluted in the water with the water: fibre ratio 8:1. The diluted fibres were mixed to homogenize the concentration in the cylinder and then the water was instantly drained. The wet-formed fibre mat was then put between the perforated boards and then placed in the hydraulic press for 5 min at room temperature at a pressure of 0.3 MPa. The pressed fibreboards were then oven dried for 24h at 103 °C.

2.3. Clay boards
For this research clay boards were acquired from two companies (Claytec and Lehmbaustoffe Schleusner). Three different types of boards were tested, (see Table 1). All selected clay board are used as a dry lining board for the internal use in practice. Boards named as Clay B14 and Clay B22 consists of sand, loam, hemp chaff and a glass fibre mesh on both sides. Another type of board (Clay Y14, Clay Y20, Clay Y25) is made of earth, clay, perlite, reed stems, hemp, jute mesh, cellulose fibres and starch < 1 %.The third type of board (Clay G22) distinguishes from other boards by its inorganic binder. The composition is clay and approx. 30% of hemp shives, the binder of the board is partly inorganic (magnesite) and organic (soybean, EU). The producers determine the densities of all boards in an average range of ~700 kg/m³.

Table 1. Overview of the tested materials

Board type and marking	Hemp F	Hemp FK	Hemp FW	Hemp S	Wood P	Clay B14 Clay B22	Clay G22	Clay Y14 Clay Y20 Clay Y25
Thickness (mm)	15	15	22	15	15	14/22	22	14/20/25
Density (kg/m³)	544.29	544.29	188.80	656.81	667.21	701.4	757.2	636.4
Photo								

2.4. Gypsum plasterboard
Gypsum plasterboards are the most commonly used lining materials. Therefore, two main types of gypsum plasterboards were additionally tested to present a comparison with clay and hemp boards. A 12.5 mm thick gypsum plasterboard type A (GtA) and a 15 mm thick fire resistant gypsum plasterboard type F (GtF) were selected.

3. Test methods

3.1. Mechanical tests
Determination of resistance to tension perpendicular to the surface of the test specimen by submitting the tensile force until the rupture occurs was done according to EN 319. Determination of bending strength was determined according to EN 310 by applying a load to the centre of the test specimen supported at two points. Determination of face withdrawal of screws was done according to EN 320 by measuring the force required to withdraw a defined screw from test piece. Mechanical tests were performed in a room temperature (23 °C) with tensile tester Instron 5866.

3.2. Fire tests
A cone calorimeter was used to expose test specimens to a predetermined external irradiance produced by the cone heater. Tests were carried out under ambient air conditions. Each test sample comprised a board that was placed on timber specimen, see Figure 1. The exposed size of the specimens was 100 mm x 100 mm. The average density of timber was 492 kg/m³.

The fire protection effect of boards was examined by measuring the temperature rise behind the board. Therefore, thermocouples were located on the exposed side in the centre and on the top surface of timber, see Figure 1. Thermocouples type K with a diameter of 0,25 mm by Pentronic AB, Sweden were used and fixed with metal staples. The specimens were maintained in a climate chamber at 20 °C and 65% RH minimum one week. The specimens were wrapped in an aluminum foil before testing. Tests were conducted using a retainer frame and specimen holder, see Figure 2.

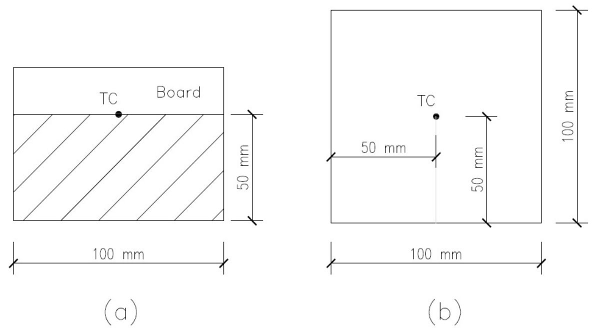

Figure 1. Set – up of test specimen: (a) cross-section; (b) top view of timber surface

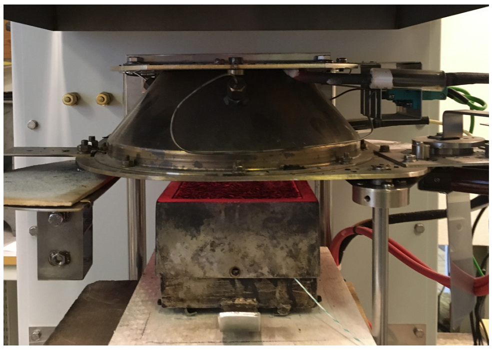

Figure 2. Fire testing of a specimen under the cone heater

The test specimen was placed directly under the cone heater for testing, see Figure 2. The distance from the bottom edge of the cone heater and the exposed surface of the test specimen was 25 mm. The specimens were subjected to predetermined irradiance levels of 50 kW/m² for the first 20 minutes, then the irradiance level was raised to 75 kW/m² for another 20 minutes. The total test time was 40 minutes. The change to a higher irradiance level was done in order to achieve a better fit to the standard fire exposure conditions expressed by ISO 834 [18]. For some test series only a constant irradiance level of 50 kW/m² was used for 20 minutes. All temperature measurements were recorded in 5 second accuracy and saved in computer. The specimens were cooled down with water after test.

4. Results and analysis

4.1. Tensile strength

From the tensile strength perpendicular to the plane of the board results (see Figure 5). It can be clearly seen that wood particleboard (Wood P) and hemp shiveboard (Hemp S) results stand out from the rest of the tested insulation boards. Hemp shive boards (Hemp S) showed the highest tensile strength perpendicular to the plane of the board (24.72 MPa), which was 30% higher than wood particleboard (Wood P). This result shows that hemp shiveboards (Hemp S) have better fiber-matrix adhesion than wood particleboards (Wood P). Hemp fibreboard (Hemp F) shows good tensile strength (0.15 MPa) and is just 40% lower than gypsum plasterboard GtA (0.22 MPa). Therefore, it can be said that hemp fibreboards (Hemp F) can be alternatives for the gypsum plasterboards. However, in the EN 622-5, wood fibreboards (12-19mm thickness) tensile strength is 0.55 MPa [19], which is 270% higher than hemp fibreboards.

When comparing the different clayboards, it can be observed that grey clayboard (Clay G22) had the 50% higher tensile strength compared to the brown clayboards (Clay B14 and B22), which can be explained with a magnesium oxide additive in the board. Yellow clayboards (Clay Y14, Y20, Y25) reinforced with reed mat had the lowest tensile strength of the clayboards due to their week interfacial adhesion between clay and reed mat. The lowest tensile strength was observed from the hemp fibreboards made with wet method Hemp FW (95% lower than hemp fibreboards made with dry method).

4.2. Bending strength

The bending strength of different natural insulation boards is shown on Figure 3. Hemp shiveboard (Hemp S) showed the highest bending strength and was 12% higher than wood particleboard (Wood P) and 55% higher than grey clayboard G22. The similar trend has been shown in the previous research by Kirilovs et al [20]. The modulus of elasticity of hemp shiveboard was 437.80 MPa and wood particleboard had 50% higher elastic modulus (670.75 MPa). (see Figure 4)

However, all of the clayboards have lower bending strength than wood and hemp particleboards. Clayboard G22 with magnesium oxide additive had the highest bending strength compared to all of the other clayboards. Yellow clayboards, which had the reed-mat reinforced clay structure, had the lowest bending strength compared to other clayboards due to their week interfacial adhesion between clay and reed mat. Hemp fibreboard (Hemp F) had about 50% lower bending strength as clay yellow board (Clay Y14). When hemp fibreboard (Hemp FK) was covered on the both sides with kraft paper, then the bending strength saw a 320% increase in bending strength and was just 28% lower than gypsum plasterboard (GtA) bending strength. When comparing the two different types of gypsum plasterboards GtA and GtF then it can be seen that fire resistant gypsum plasterboard GtF has 40% higher bending strength due to the different fire resistant additives. The highest modulus of elasticity was observed with the gypsum plasterboards, which mean that these materials are a lot stiffer than all the other natural insulation materials that were tested.

The hemp fibreboard made with wet method (Hemp FW) had the lowest bending strength which was 150% lower than hemp fibreboard made with urea-formaldehyde glue (Hemp F). When looking at the standard requirements (EN 622-4) for the wood based softboards with a thickness over 19 mm, then bending strength requirement is 0.8 MPa. In this research, the average bending strength for hemp fibreboards (Hemp FW) was 0.31 MPa which is 61% lower than wood soft fibreboards. This can be explained by the higher lignin content and therefore better wood fibres bonding [21][22].

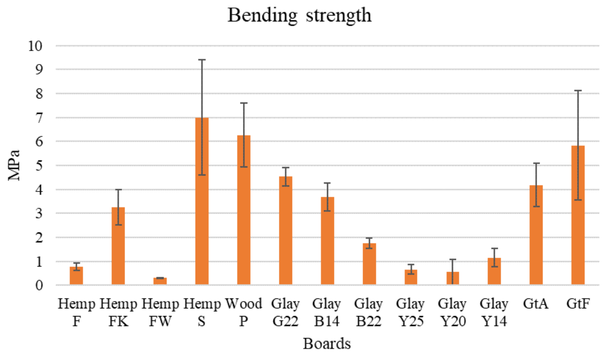

Figure 3. Bending strength of different insulation boards

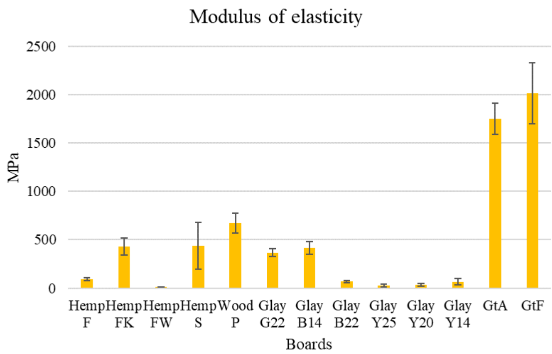

Figure 4. Modulus of elasticity of different insulation boards

4.3. Resistance to axial withdrawal of screws

The results of the axial withdrawal of screws is given in Figure 6. The results show that the hemp shive board, wood particleboard and clay board reinforced with wood particles (G22) had the highest resistance to the axial withdrawal of the screws. The highest screw withdrawal strength was obtained with the wood particleboard (Wood P) which was 26% higher than hemp shiveboard (Hemp S) screw withdrawal strength. This can be explained with the higher density of wood and lower density of hemp. Clayboards reinforced with reed mat had the lowest resistance to the screw withdrawal due to their week interfacial adhesion between clay and reed mat. When comparing the hemp fibreboard (Hemp F) as an alternative to the gypsum plasterboard (GtA) then it can be seen that hemp fibreboard has 40% higher screw withdrawal strength which indicates the stronger adhesion between fibres and glue than in gypsum board. However, the resistance to axial withdrawal of screws from wood softboards in EN 622-4 [23] is required of 30 N/mm, which is 150% higher than the hemp fibreboards results in current research.

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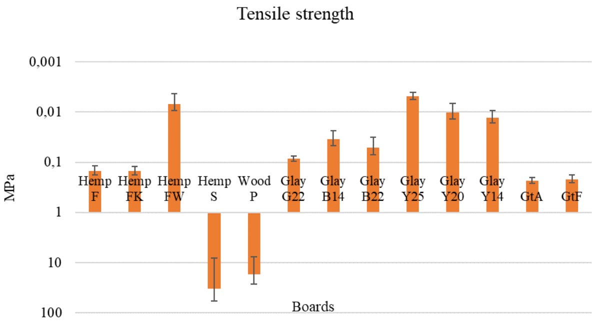

Figure 5. Tensile strength perpendicular to the plane of different insulation boards

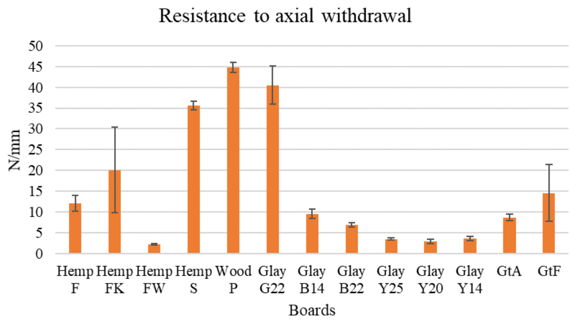

Figure **6.** Resistance to axial withdrawal of screws

4.4. Fire performance

A total of 16 specimens were tested. Selectively double tests were conducted to ensure the reliability of test results. The hemp (Hemp S) and wood particleboard (Wood P) demonstrated a significant deformation and shrinkage at high temperatures. This is probably related to the same preparation technique and the used adhesive in both boards. The hemp board with kraft cover (Hemp FK) showed minimal deformation and less shrinkage. Hemp FW totally decomposed. The clay boards retained their solid structure and neither deformation nor significant shrinkage was observed. After extinguishing with water, majority of the boards (except Clay G22, Hemp FW) did not decompose.

The main attention was paid on the temperature measurements recorded at the interface between the board and timber. The temperature values of 270 °C and 300 °C were in special interest since these values are agreed to be taken as the basic protection time of a material (t_{prot}) [2] and the start time of charring of timber (t_{ch}) [1]. The values were pinpointed from the temperature recordings, see Table 2. Furtermore, the ignition time and mass loss of boards were detected.

Table 2. Test results for boards

Board type	Ignition time (sec)	Weight of board before test (g)	Mass loss rate by 100 °C (%)	Basic protection time t_{prot} (min)	Start time of charring of timber t_{ch} (min)
Hemp F	25	92.5	43.2	22.3	23.5
Hemp FK	13.5	94.9	51.8	28.1	30.1
Hemp FW	5	44.1	38.5	14.6	16.0
Hemp S	24.5	98.0	40.1	21.2	22.8
Wood P	35.5	103.3	33.3	16.6	17.8
Clay B14	No	98.3	6.3	8,5	10
Clay B22	No	131.2	8.7	22.5	25.9
Clay G22	No	170.1	15.2	37.5	> 40
Clay Y14	No	89.1	n/a	10.1	11.8

The average temperature measurements for clay and hemp boards are illustrated in Figure 7. The lower temperature curves present better fire protection ability. Thicker boards show better performance; the plateau at 100 °C refers mainly to the water evaporation that delays the temperature rise behind the boards. Clay boards (14 mm) show similar behaviour despite their differences in composition. Hemp boards demonstrate different protection effects, e.g. hemp boards with a kraft paper (Hemp KF) present significantly better fire performance compared to other boards. The temperature rise is the fastest behind the hemp fibreboard made by wet method (Hemp FW) that corresponds to its significantly lower density and faster combustion.

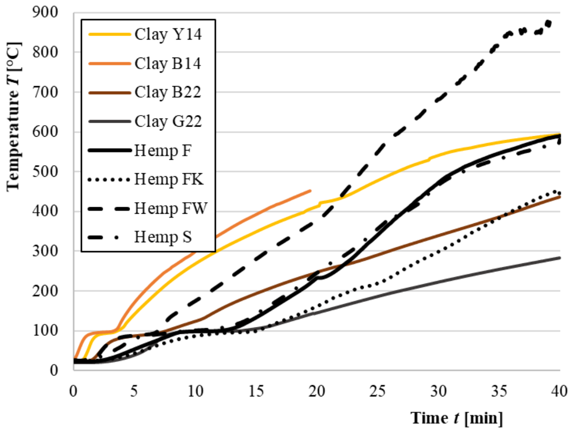

Figure 7. Temperature measurements behind clay and hemp boards on timber

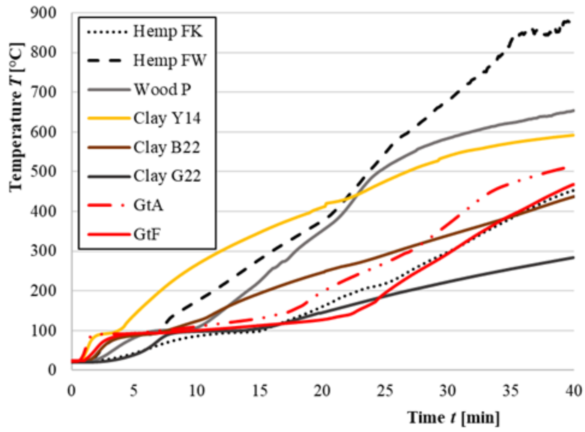

Figure 8. Comparison of temperature measurements behind different boards on timber

For reference, a comparison to GtA and GtF is presented in Figure 8. The hemp fibreboard covered with paper (Hemp FK) shows similar performance to the gypsum plasterboards, whereas the clay board (Clay G22) presents even a better fire protection ability. This indicates that additives in clay boards can significantly increase its fire resistance. All tested hemp boards demonstrated better protection ability compared to the wood particleboard (Wood P) within the most relevant temperature range of 270–300 °C. Further work is needed to confirm the results in larger scale that also enables to investigate the integrity of the boards and the fall-off time.

5. Conclusion

It was shown that hemp fibreboard and particleboard are adequate alternatives for the clay boards and gypsum plasterboards. When the hemp fibreboard is covered with kraft paper, it is possible to have similar mechanical and fire properties to the gypsum plasterboard. However, the hemp fibreboard made by wet method had the weakest mechanical and fire properties and should be more investigated. The production method of hemp boards has a significant influence on its fire protection ability. Additives can enhance the fire resistance of clay boards. Fire tests in larger scale are needed to confirm results and provide further knowledge.

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