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## ASSESSMENT OF STRUCTURE INFLUENCE ON THERMAL CONDUCTIVITY OF HEMP SHIVES COMPOSITE

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### Abstract

In past ten years area of green technologies and materials was the most growing industry sector in the world. It is related with global warming, air pollution and energy saving. Building sector intensively increased air pollution and is related with high energy consumptions. The use of renewable or recyclable materials can reduce these problems.

In current work, thermal insulating materials from hemp shives and corn starch were investigated. Structures of various shives fractions were analyzed. Different sized shives by two indicators bulk density and thermal conductivity were compared. Composite materials with various shives fractions and corn starch were prepared. Different thermal treatment for composite hardening was used. Thermal conductivity and compressive strength of composites were determined. Thermal insulating composites with a high compressive strength and low thermal conductivity were developed.

*Key words:* corn starch, ecological building materials, hemp shives, renewable resources, thermal insulating composite

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### 1. Introduction

Buildings represent the largest energy consumption sector in the economy, with over one third of all energy consumed there. As a result they are also responsible for approximately one – third of global carbon emissions (Technology Roadmap, 2013). Transformation of raw materials into constructional materials generates roughly 50% of all atmospheric emissions of CO<sub>2</sub> (Medineckienė et al., 2010). The development and exploitation of eco materials can to a certain degree reduce humankind's demand for natural resources, substitute environment-friendly products in place of pollutant products, and raise the efficiency of resources utilization and save natural resources through reproduction and cyclic utilization of materials (Qiu, 2011). The construction sector has a major environmental impact due to resulting waste, occupation of land, air pollution and influence on

biodiversity. This requires new approaches in the construction of buildings and the manufacture of building materials (Aciu and Colbirzan, 2013).

In recent years, cheaper alternatives to traditional building materials have been increasingly used as a way of lowering building costs. For example, instead of natural woods, pressed-wood products and fiber board are used. While cheaper is definitely good economically, it can be bad for human health. These synthetic materials emit volatile organic compounds (VOCs) or other hazardous air pollutants that may cause the nausea, dizziness, headaches, skin rashes, lethargy and skin and nose irritation (James and Yang, 2005).

Composites from vegetable raw materials are not harmful to the environment as well as to human health. Composites from renewable materials can become harmful to the environment if harmful binders and additives are used. So it is important to properly choose necessary components.

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In order to reduce air pollution and climate change, environmental requirements are constantly increased. Stricter requirements are determined for production of thermal insulation materials – ozone depleting substances are forbidden or gradually reduced, use of human health harmful additives (such as antiseptics and flame retardants) and binders (such as phenol formaldehyde resin) are restricted or prohibited (Velders et al., 2007).

The easiest way to build environmentally friendly buildings is when renewable resources are used (Mora, 2007). To build sustainable and affordable buildings for the future, it is necessary to create links between the agricultural and construction industries (Kidalova et al., 2012).

The use of renewable materials in building construction is useful for the environment and people considering finance and quality (Medineckienė et al., 2010). More sustainable building materials therefore have the potential to have a large impact on global environmental problems (Mukherjee, 2012). In the production of traditional thermal insulating or thermal insulating – structural materials, large amount of energy is used as well as high emission of ozone – depleting gases are eliminated. For example in order to produce 1 ton of mineral wool, from 7 GJ to 20 GJ of energy is used and manufacturing process emits from 0,57 to 0,74 ton of CO<sub>2</sub> (Ecofys, 2009). Traditional thermal insulating - structural materials, for example expanded clay concrete, ensure necessary mechanical properties for the envelopes installation in low rise or multi – storey buildings, but their manufacturing technology is very energy intensive. Light weight expanded clay aggregates are produced from clay, waste brick powders, albite floatation waste, and coal at various temperatures ranging from 900 °C to 1250°C (Arioz et al., 2008).

For the production of thermal insulating and thermal insulating – structural materials, various renewable resources are used: hemp, flax, jute, different kind of wood (Gonzalez-Garcia, 2012). The woody core part of the hemp stalk called shives or hurds is considered as a waste in the hemp industry (Stevulova et al., 2013).

According to literature data, due to the low density and high porosity of the hemp shives, the combination of hemp shives and binder creates a building material with good thermal and acoustic insulation properties (Kidalova et al., 2011, 2012).

The hemp shives serves as a lightweight aggregate, with a low bulk density and a large volume of trapped air within its pores (Duffy et al., 2013). By the method of 3D tomography foreign scientists had determined that porosity of hemp hurds was of 57 %. The size of pores formed between the particles depends on the texture of hurds and it is about 1 mm. The inner porosity of hemp hurds consists of 15 % of 70 μm sized pores and 85 % of 400 μm pores (Ceyte, 2008). Hemp hurds are suitable for the production of thermal insulation composites due to their cellular structure consisting of small

pores, therefore, good strength and thermal properties can be achieved.

Hemp shives are often used as a lightweight aggregate for hempcrete production. For the production, different binding materials are used:

- lime (Arnaud and Cerezo, 2001; Bruijn et al., 2009; Elfordy et al., 2008; and others);
- cement (Bruijn et al., 2009; Tran et al., 2010);
- sapropel (Balčiūnas et al., 2014; Pleikšnis and Dovgiallo, 2013).

Tow of flax and hemp fibers has traditionally been used in insulation tapes between timbers, but during the past decade several types of mats and loose-fill insulations have been developed into commercial products. Loose-fill insulations and insulation sheets of different thickness are also produced for insulation of modern houses. Despite their historical background, flax and hemp insulations are often considered as new materials in the field of insulations (Kymalainen and Sjoberg, 2008). Chopped hemp is frequently used as a loose insulation material, although it requires treatment with borax salts or other materials to ensure that fire risk is minimized (Kidalova et al., 2012).

Analysis of literature sources has shown that production of effective building materials from renewable resources is very important to ensure environmental requirements, to save human health and minimize the use of energy. Another important task is to find new effective binding materials, which are friendly to an environment in the phase of their production and disposal at the end of life cycle. Starch is one of the least expensive biodegradable materials used for many non-food items such as paper making, card board, textile sizing and adhesives.

The aim of this work is to develop effective thermal insulating and thermal insulating-structural materials from local renewable resources.

## 2. Materials and methods

In tests, hemp shives were used as loose fill insulation and lightweight aggregates. Fiber hems were grown in the north of Lithuania. In the experiments, the hemp species USO-31 were used. Hemp shives were obtained after initial mechanical processing. Fractioned (0/2.5; 2.5/5; 5/10; 10/20 mm fractions) and mixed shives fraction were used. Particles larger than 20 mm were additionally chopped.

Corn starch was used as a binder (supplier ROQUETTE FRERES, France). Morphological structure of particles of corn starch is shown in Fig. 1. Physical and chemical properties of corn starch are follow: physical state – white, neutral odor, powder density of approx. 0.50 kg/L; non-toxic, biodegradable product, environmentally friendly material, can be eliminated as a solid waste; auto ignition temperature is 480°C; insoluble in water at 20 °C; soluble in water at 90 °C; stable with respect

to storage conditions. Corn starch is characterized by the granules separation.

Five different forming mixtures were formed. Forming mixtures of composite are shown in Table 1.

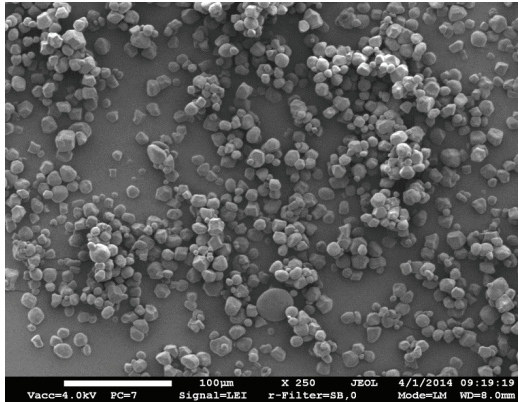


Fig. 1. Morphological structure of corn starch particles (magnification 250x)

### 2.1. Compressive strength

For compression tests, 5 specimens – cubes were prepared of each composition with dimensions of (100x100x100) mm were formed. Before testing specimens were conditioned for 72 h at 23±5 °C temperature and 50±5% relative humidity conditions. Compression tests were carried out in accordance with EN 826:2013 requirements. Compressive strength  $\sigma_{10\%}$  and stress-strain curve were obtained for each tested specimen. Compression tests were carried out using testing machine H10KS Hounsfield (England); the loading rate was of (0.1·d) mm/min, where “d” is thickness of sample, the error of the meter varied from 1 N to 11 N. The tests were conducted at ambient temperature (23±5) °C and relative humidity (50±5) %.

### 2.2. Thermal conductivity

For thermal conductivity test, loose fill hemp shives and shives/starch composites with dimensions of (300x300x60) mm were used. One specimen for each fraction/composition was measured in two different conditions. Firstly, before testing specimens were dried at 105±2 °C to a constant mass, further, before testing specimens were conditioned at 23±5 °C temperature and 50±5% relative humidity conditions to constant mass.

Prepared forms were filled with loose shives. In both cases initial loading of 500Pa was used to get better contacts between plates of instrument and specimen faces. Thermal conductivity tests were performed using heat flow meter apparatus FOX 304 (LaserComp, USA). Measurement range of the apparatus is from 0.5 W/(m·K) to 0.004 W/(m·K) with a centrally located heat flux transducers having dimensions of (100x100)mm. Absolute accuracy of thermal conductivity measurements was less than ± 1.5%.

Thermal properties of materials were measured in accordance with EN 12667 and ISO 8301.

### 2.3. Bulk density

The density of hemp shives was determined based on methodology for the measurement of granular insulation materials’ density (Fig. 2). For determination of the density, the cylinder (3) with a diameter of 225 mm, a metal plate (1) and needle calipers were used (2). It was weighed (200±1) g of hemp shives and they were placed in the cylinder, which is placed on a metal plate (Fig. 4). The thickness measurement equipment having the loading capability from 50 Pa to 2000 Pa with needle was inserted into the cylinder with hemp shives. Each loaded specimen was kept in the cylinder for 5 minutes.



Fig. 2. Equipment for bulk density measurement (1 - metal plate, 2 - needle caliper, 3 – cylinder)

Table 1. Forming mixtures of the composite

Mix. No.	Hemp shives fraction, (mm)	Hemp shives (%)	Corn starch content by dry mass of shives, (%)	Water content by dry mass of shives, (%)
1	0*/2.5	28.6	14.3	57.1
2	2.5/5	28.6	14.3	57.1
3	5/10	28.6	14.3	57.1
4	10/20	28.6	14.3	57.1
5	0/20**	28.6	14.3	57.1

\* - 0 value means bottom of sieves set

\*\* - 0/20 – is not fractionated hemp shives. Shives which are bigger than 20 mm fraction and fibre refuses are removed

Hemp shives density was calculated from (Eq. 1):

$$\rho_0 = \frac{m}{0.785 \cdot D^2 \cdot h} \quad (1)$$

where:  $m$  is the weight of hemp shives specimen (200 g);  $D$  is the diameter of the cylinder (22.5 cm);  $h$  is the hemp shives layer thickness in cylinder after loading.

#### 2.4. Microstructure

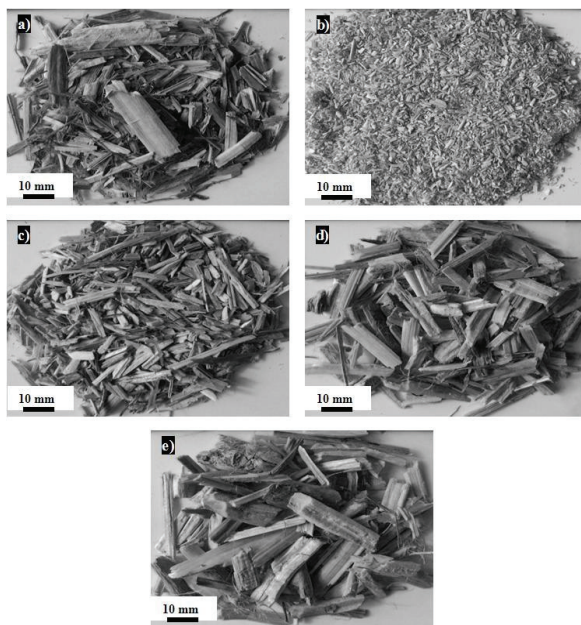
The morphology of hemp shives particles and microstructure of sample of corn starch (Fig. 1) and hemp shives was investigated using SEM „JEOL JSM-7600F“ (Japan), resolution – 1.5 nm, sample was coated in vacuum with the conductive carbon layer, accelerating voltage was of 20.0 kV.

The structure analysis was carried out by examining cross-sectional surface of the hems shives. The flat area of the specimens was examined by “UTHSCSA Image tool” software.

### 3. Experimental results and analysis

#### 3.1. Macrostructure

After mechanical processing of hemp straws, various fractions of shives and fibers were obtained. During processing, long and short fibers were separated from shives. Immediately after mechanical processing, shives particles highly differed in terms of the size (Fig. 3a). In order to ascertain properties of different size particles, hemp shives were fractionated through sieve column.



**Fig. 3.** View of fractionated shives: a) – 0/20 mm (non fractionated); b) – 0/2,5 mm fraction, c) – 2.5/5 mm fraction, d) – 5/10 mm fraction, e) – 10/20 mm fraction

View of fractionated shives is presented in Fig. 3b-e. As it can be seen from Fig. 3, shives with the fraction of 0/2.5 differ in size a lot. After visual observation it was noticed that this fraction consists from dust, small particles of fibers and shives. Visually no spaces between particles were observed. Other fractions 2.5/5, 5/10 and 10/20 differ from one another just in size of particles and space between particles. Otherwise, quantity of these fractions is different as well. Quantity of fractions is presented in Table 2.

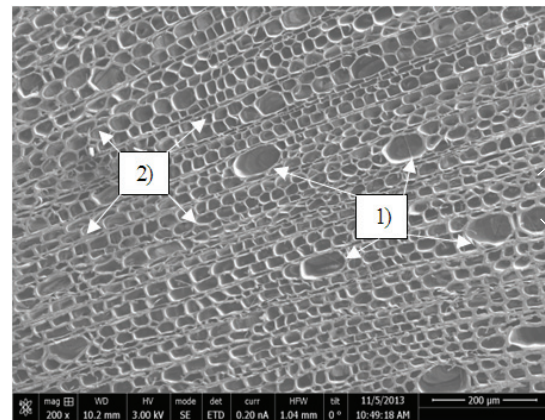
**Table 2.** Hemp shives fractions quantity by mass

Fraction size, mm	Quantity, %
0/2.5	12.2
2.5/5	16.0
5/10	46.0
10/20	13.8
>20	12.0

Almost half of weight of all fractions consists of the fraction 5/10 mm. Proportion by mass of other fractions differs only slightly. The largest fraction on the sieves was 20/40 mm i.e. during the sieving, all shives poured out through the holes having a size of 40 mm. The rest small amount of hemp shives which were left on the 40 mm sieve were additionally chopped and sieved. The main indicator for thermal insulating materials' on which heat transfer depends is materials' density; therefore, bulk densities of various shives were determined.

#### 3.2. Microstructure

Mechanical and thermal insulating properties of materials highly depend on micro- and macrostructure. Microstructure of conventional insulating materials is mainly porous or fibrous. Hemp shives have porous microstructure, which is close to the microstructure of open cell polymer foam (Fig. 4).



**Fig. 4.** Microstructure of hemp shives perpendicularly to the plane of growing direction. 1) – First type pores (vessel), 2) – Second type pores (xylem ray), magnification x200

Hemp shives structure is porous perpendicularly to the plane of growing direction (two different sizes pores 1 (so called vessel) and 2 (so called xylem ray (Amaducci et al., 2015) may be seen). The pores of first type have the form of ellipse; the length of longer ellipse axis is averagely of 85  $\mu\text{m}$  and shorter ellipse axis is of 45  $\mu\text{m}$ . The pores of second type are of various forms, i.e. ellipse, rectangle, circle; average diameter of the pore is of 25  $\mu\text{m}$ .

As it can be seen from Fig. 5, there are two types of pores in the plane parallel to the growing direction as well, i.e. close to the form of ellipse and rectangle/rhombus. The pores of the first type have the form of ellipse; the length of longer ellipse axis is averagely of 345  $\mu\text{m}$  and shorter ellipse axis is of 37.5  $\mu\text{m}$ . The pores of second type are of various forms, i.e. ellipse, rectangle, circle; average diameter of the pores is of 45  $\mu\text{m}$ .

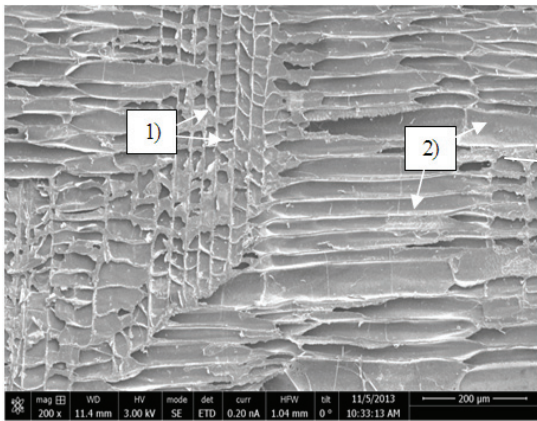


Fig. 5. Microstructure of hemp shive in the plane parallel to the plant growing direction. 1) – First type pores (Vessel), 2) – Second type pores (Xylem ray), magnification x200

As it can be seen from Fig. 6, the walls of pores are cellular as well. Cells in the walls have the form of the circle with the diameter of 2.5  $\mu\text{m}$ . Small cells not only reduce weight of hemp shives, but also the area of contact zones.

Fig. 7 shows the contact zone between hemp shives and binding material. This zone is sufficiently even, however, the voids in the composite can be seen as well. These voids form due to irregular form of the shives. The width of contact zone in the cross-sectional plane varies from 15  $\mu\text{m}$  to 120  $\mu\text{m}$ . Composite formation with small contact zones leads to lower thermal conductivity of material.

### 3.2. Physical properties

The physical properties of composite characterize the usage area of material. Density is an important parameter for the composite from hemp shives when it is used as thermal insulating or structural material. Bulk densities of fractioned and not fractioned shives are presented in Fig. 8.

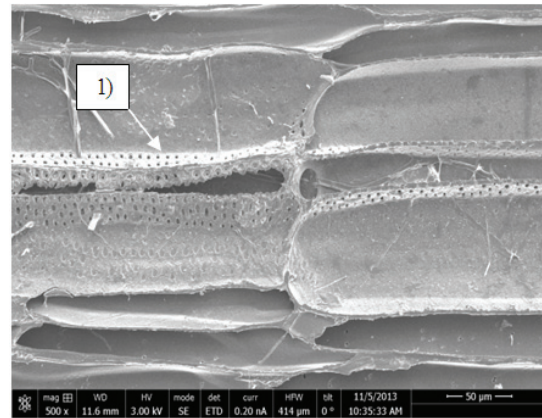


Fig. 6. Microstructure of hemp shive in the plane parallel to the plant growing direction. 1) - Cellular wall of the pore, magnification 500x

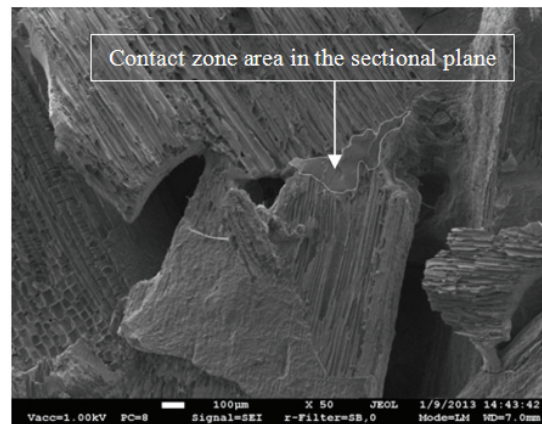


Fig. 7. Contact zone of hemp shives and starch binding material (magnification x50)

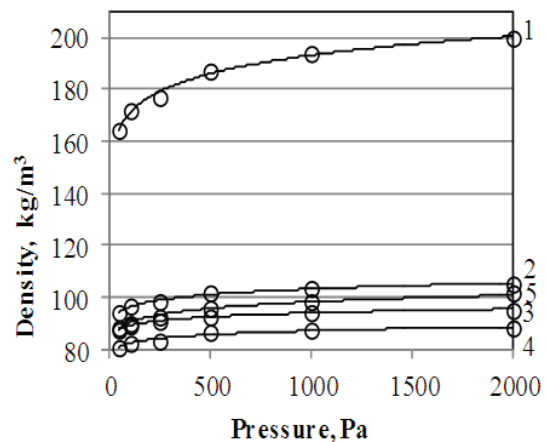


Fig. 8. Load size influence on density, when fractions in mm: 1 – 0/2.5; 2 – 2.5/5; 3 – 5/10; 4 – 10/20; 5 – 0/20 (non fractioned)

In Fig. 8, we can observe that the bulk density is high when the shives size is small. The greatest difference is observed in the smallest fraction. The density of this fraction is about 2 times larger than

that of the other fractions. There are two reasons for this phenomenon: 1) the smallest particles fill air gaps between large particles 2) bulk density of small fibers is higher compared to the shives density. The density of not fractioned shives is in the middle of the graph.

Shives densities under various loads vary differently. Using initial loads up to 500 Pa, sudden increase in density is observed. This can be explained by orientation of particles, where empty air cavities are filled. Increasing the load, the growth of density rapidly decreases. It means that the cavities filling process is completed, but the deformation and compaction of particles only start. Loading above the 500 Pa, the distribution is close to straight line. In case of 0/2.5 fraction the initial growth of density is more intensive. Using the loads from 50 Pa to 500 Pa, the density increases by  $23 \text{ kg/m}^3$ , and, in the case of other fractions, by approximately  $10 \text{ kg/m}^3$ . It means that particles having small sizes better fill air cavities; moreover, particles of 0/2.5 mm are softer.

Other indicator for evaluation of particles size differences is thermal conductivity. For evaluation, air-dried and dried shives were used. As it can be seen from Fig. 9, the highest thermal conductivity of the fraction 10/20 is observed.

Greater shives particles form big air cavities in loose-fill material, leading to a greater thermal transfer by gas.

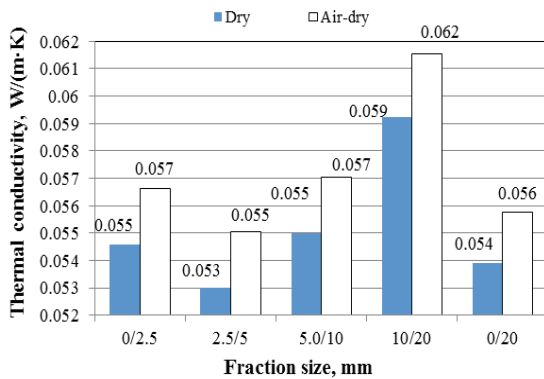


Fig. 9. Thermal conductivity of various size hemp shives (loose fill)

Other fractions show similar results – test results vary from  $0.053 \text{ W/(m}\cdot\text{K)}$  to  $0.055 \text{ W/(m}\cdot\text{K)}$  in dry conditions and from  $0.055 \text{ W/(m}\cdot\text{K)}$  to  $0.057 \text{ W/(m}\cdot\text{K)}$  in air-dry conditions. The most interesting fraction from the scientific point of view is 0/20 (non fractioned). Most likely, smaller fractions deploy between larger ones; smallest particles improve the contact zones between particles and influencing the increase in heat transfer by solid materials frame. In all cases, thermal conductivity of air-dried shives is higher by about 4% than dried ones. It is likely, that negligible moisture content increase heat transfer by gas, which increases density due to the moisture; moreover, the moisture content improves contact zones between hard particles.

The obtained lowest thermal conductivity values are close to the thermal conductivity of effective modern thermal insulating materials. The thermal conductivity of composite from hemp shives and starch binder varies in accordance with the same tendencies as sole shives.

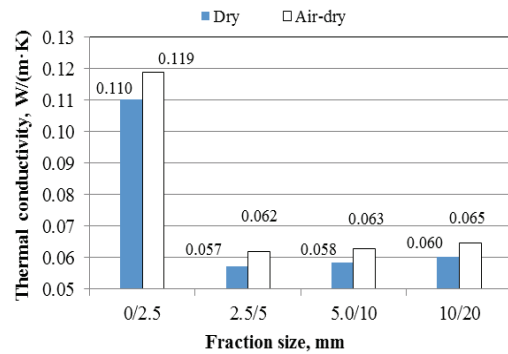


Fig. 10. Thermal conductivity of composite material from various size hemp shives and starch binder

As it is seen from Fig. 10, the highest thermal conductivity is obtained for composite having the fraction of 0/2.5 mm. Thermal conductivity of the composite from the finest fraction hemp shives is the highest due to the higher bulk density and surface area of the mentioned fraction. For this reason, the content of contact zones highly increases leading to the greater heat loss through the solid carcass. Comparing the values of thermal conductivity of hemp shives and composite from hemp shives with the starch binder, it can be seen that addition of a binder has increased the thermal conductivity of thermal insulating material hardly noticeably.

This is determined by appropriate selection of binder content which slightly increases the contact zones area. When 0/2.5 mm fraction shives as an aggregate are used, we can observe clearly visible cracks (Fig. 11), which are formed during the hardening process of composite. The cracks are formed due to short shives, which as reinforcing material are not sufficiently effective.



Fig. 11. Cracks which formed on the composite surface during hardening process, when the 0/2.5mm fraction was used

Densities of composite material specimens, which were used for thermal conductivity measurement (with fractions of (2.5/5, 5/10, 10/20) mm), are similar. Densities of the previously mentioned fractions vary from 210 kg/m<sup>3</sup> to 230 kg/m<sup>3</sup>. Density of the smallest fraction is significantly higher and is about 420 kg/m<sup>3</sup>.

To ensure that hardening schedule (24 h at 185 °C temperature) of forming mixture was selected appropriately, compressive strength of composites hardened at difference temperatures (165 °C, 185 °C and 205 °C) was determined (Fig. 12).

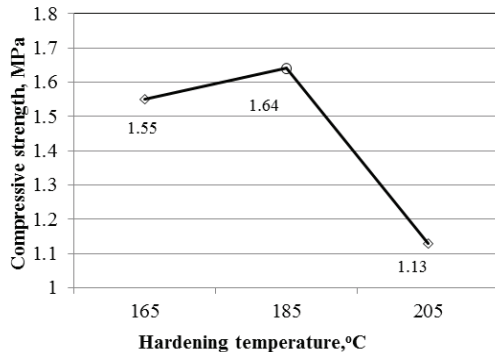


Fig. 12. Hardening temperature influence on composite compressive strength (densities of specimens (250±10) kg/m<sup>3</sup>)

Hardening at the temperatures of 165°C and 185°C does not have a great impact on the compressive strength of the composite. However, at the temperature of 205 °C a significant reduction in compressive strength (by 27-34%) is observed. Hardening temperature of 205°C was chosen in order to shorten the hardening time. However, while starch, which is located in the internal layers of the composite material, proceeds to the phase of dextrin, the contact zones, which are located in the external layers, weaken due to the burning process.

Compressive strength at the hardening temperature of 205°C reduces regarding to the burning of organic materials located in contact zones of composite and shives.

#### 4. Discussion

Analysis shows (González-García et al., 2012) that various quantities of plants are used for thermal insulation materials or as light aggregates for composite materials production. In most cases, analysis of mechanical properties of such materials has not been done. It is related to soft materials frame and very low overall compressive strength. To get high materials strength compression, large amount of binder must be used or the frame of raw material must be enough hard. In our case, hemp shives are hard particles with highly cellular microstructure.

Macrostructure is defined by the structure between hemp shives. The information about thermal conductivity and compressive strength ratio has not been found. In this case, these parameters can play

essential role, because they show differences between thermal insulating or thermal insulating-structural materials. Scientists (Arnaud and Cerezo, 2001; Bruijn et al., 2009; Elfordy et al., 2008) have analyzed hemp shives/lime composites. Such composites are very ecological because of low CO<sub>2</sub> emission. Otherwise, hemp shives/lime composite has low strength (about 10 times lower than our composite) and higher thermal conductivity (about two times than our). Other binders were analyzed by scientists (Bruijn et al., 2009; Stevulova et al., 2012; Tran et al., 2010).

Composites with cement binding material are of high density and higher thermal conductivity (about 2 times than our composite), but compressive strength is sufficiently high - up to 5.2 MPa. The production of such materials is of low labor and cost consumption. When the hemp shives/starch composite is used in building envelopes, it is possible to use it without additional insulation layer giving the required thermal resistance.

#### 5. Conclusions

1. Hemp shives with and internal cellular microstructure may be used as loose-fill thermal insulation material and as a light-weight aggregate for the production of thermal insulation or thermal insulation-structural composites.

2. Properties of different shives fractions are different in evaluation of bulk density and thermal conductivity. Shives that are greater than 5 mm have higher thermal conductivity, thus they must be additionally mechanically chopped. Because of the high surface area, the shives fraction from the 0 size sieve have two higher density, therefore, they cannot be used as loose-fill insulation or as an aggregate for the production of composites.

3. For the hardening of composites, rational regime of hardening temperature must be chosen. When the temperature is too low, the starch particles poorly bind shives particles, i.e. starch does not proceed to the phase of dextrin. When the temperature is too high, it can be assumed that the internal decomposition of contact zones starts due to the burning process.

4. The fraction of 0/2.5 mm is not suitable as an aggregate for the production of composites because of the low compressive strength. During the visual observation, cracks were noticed. They occur during the hardening due to the shrinkage of the binding material, i.e. fine aggregates (particles of fibers and shives) are not effective in terms of reinforcement.

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