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Ecological, thermal and acoustical insulating composite from hemp shives and sapropel binder

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ABSTRACT

The technological parameters for the production of hemp shives (HS) composite with organic sapropel binder and reinforcement additive – paper production waste (PPW) is developed and properties of this composite are investigated in this paper. The amount of sapropel in composite was 5% of HS mass by the amount of dry materials. Thermal processing with highest temperature of 190 °C was used for hardening of the composite. The thermal conductivity and sound absorption coefficients, compressive stress, short-term water absorption, water vapor diffusion resistance factor of composite were investigated. The impact of various factors on the properties of composite was evaluated. The greatest impact has the compaction level of composite, also PPW additive. The impact of HS particles size ranging from 2.5 mm to 20 mm is much smaller. The regression equations enable prediction of thermal conductivity and compressive stress of composite depending on density and HS particles size were derived. The impact of surface hydrophobization on short-term water absorption was evaluated. Compared to HS-lime composite, better thermal and acoustic properties of HS-sapropel composite were obtained.

To build environmentally friendly, sustainable and energy efficient houses, it is expedient to form connections between agriculture and the construction industry (Bruijn et al., 2009). Sustainable housing can only be built when renewable resources are used (Mora, 2007). The industry of thermal insulating materials increasingly uses the following renewable resources: hemp, flax, jute, straws, different types of wood (González-García et al., 2012). Hemp is especially important as it hemp can produce high annual yields of biomass (>10 t/ha) (Finnan and Styles, 2013). The hemp which is known as industrial hemp or non-drug hemp refers to the Canabis sativa species, which has low amount of tetrahydrocannabinol (THC) (Small and Marcus, 2002). The hemp is an easily adaptable plant and has a large diversity of species (Mankowski and Kolodziej, 2008). A hemp stem, depending on a specific species, contains approximately 20–40% (by mass) of fibres on a stem surface, and about 60–80% (by mass) of woody core (shives) inside of stem (Vogl et al., 1996; Thygesen et al., 2005). There are variations in morphological aspects of the hemp stems between early and late growth phases (Liu et al., 2015). Both the hemp fibres and the shives are suitable for the manufacture of composite thermal insulating materials. George et al. (2015) have found that chemical treatment of hemp fibres, such as mercerization prior to enzymes can be an effective method for improving the thermal and surface properties of fibres for composite applications. The mechanical performance of composites can be improved by an alignment of discontinuous fibres (Pickering and Aruan Efendy, 2016). The scientists (Korjenic et al., 2011) have analysed the material made of hemp fibres, shives and the binder (bicomponent fibres). This material has low thermal conductivity (0.0393 W/(m K) and 0.0486 W/(m K)) at the densities of 40.3 kg/m^3 and 77.9 kg/m^3, respectively. The hemp shives (HS) have fine porous structure. Additionally, they are about 4 times less expensive compared to the hemp fibre (Hemptraders, 2016). HS as loose-fill material are characterised by 2 types of porosity, i.e. the intra-particle (shive) porosity and the inter-particle porosity (Glé et al., 2011). The intra particle HS porosity, determined using a 3D tomography, is approximately 57%. About 15% of pores have a size

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of approximately 70 μm, while 85% of pores are 400 μm (Ceyte, 2008). The size of inter-particle pores depends on the HS granulometry and is averagely 1 mm. HS are often used as aggregates in the manufacture of hemp concrete. The investigations (Elfordy et al., 2008; Evrard, 2003; Arnaud and Cerezo, 2001; Cerezo, 2005) show, that the hemp concrete with lime binder has the densities ranging from 256 kg/m^3 to 782 kg/m^3, the values of compressive strength varies from 0.2 MPa to 1.2 MPa and Young‘s modulus from 3 MPa to 90 MPa. The concrete with the densities ranging between 417 kg/m^3 and 551 kg/m^3 has the thermal conductivity between 0.179 W/(m K) and 0.485 W/(m K) (Elfordy et al., 2008).

To produce ecological materials, an ecological binder must be used. One of such environmentally friendly and non-harmful to human health binders is sapropel. The term of Greek origin “sapropel“ was first mentioned in the scientific literature in 1901 by the German researcher Lauterborn (Fenchel and Finlay, 2010). Sapropel is a centuries old mud of colloidal structure, formed in the benthic zone of lakes in anaerobic conditions. The colloidal sapropel structure is predetermined by the prevailing organic materials, mainly humic acids. Sapropel also contains mineral materials brought by water flowage which determine its specific chemical and physical properties. The natural moisture content of sapropel ranges from 70% to 98%. The layers of sapropel in the muddy Lithuanian lakes and bogs are about 8–12 m in thickness. The sapropel is classified into organic (when the amount of ash is <30%) and non-organic (when the amount of ash ranges from 30% to 85%) (Bakšienė and Ciūnys, 2012). However, only the organic sapropel has binding properties, which are predetermined by humic acids (Žvironaitė et al., 2002). The Latvian scientists (Pleikšnis and Dovgiallo, 2013; Pleiksnis et al., 2015) have analysed sapropel as a binder in the manufacture of thermal insulating HS composites. They have used the organic sapropel, containing 5.66% of dry materials. The obtained HS and sapropel composites are characterised by thermal conductivity ranging from 0.0605 W/(m K) to 0.051 W/(m K) when the densities vary from 112 kg/m^3 to 196 kg/m^3. However, the compressive strength of these composites is very low and ranges from 16 kPa to 148 kPa.

The samples have been compacted during formation and hardened at the laboratory conditions (20 °C and 40% relative humidity). The detailed analysis of the influence of compaction level and hardening temperature on the properties of composite has not been performed yet.

Investigation of the thermally hardened sapropel-based composites is presented in this paper. Water filters waste from paper production (PPW) is used as a reinforcing additive. The influence of technological parameters (HS granulometry and compaction level) and reinforcing additive on the physical, mechanical, thermal insulating and other important performance characteristics (sound absorption, water absorption, water vapour permeability) of the composite is analysed.

1. Materials and methods

1.1. Sapropel

The organic sapropel from Kerėplis lake (Lithuania) is used. It has been taken out from a depth of 3–5 m. Water content in sapropel of natural state is approximately 92%, the content of organic materials in a dry sapropel is 96.5%. To improve its binding properties, the wet sapropel is passed through a blender.

1.2. Hemp shives

HS of USO 31 variety is used. Hemp is harvested at the maturity of seeds in eastern Lithuania. The hemp stems are processed in toothed shafts MLTU-6A (Ukraine). The fibres are separated from a woody stem, and the woody stems are crushed in order to obtain HS. HS are fractionated using sieves. The HS sizes (mm) of 2.5/5; 5/10; 10/20; >20 have been used.

1.3. Reinforcing additive

The sapropel of colloidal state contains high amount of water. When sapropel dries, high shrinkage deformations occur. The previous research (Balčiūnas et al., 2014) has demonstrated that these deformations might be decreased with the help of reinforcing additive – PPW. The main component of PPW is fine fibres of cellulose, set on the walls of filters (~75%). The humidity of PPW ranges from 58% to 70%. For the preparation of composites, the PPW has been passed through a blender together with sapropel.

1.4. Hydrophobization

Due to the open porosity structure of HS, the composites feature high water absorption. To decrease water absorption, the composite surface is sprayed with the hydrophobizing agent Beiphob FR. This is a white liquid having the density of around 1000 kg/m^3 and pH of 4–5. After the hydrophobizing agent is sprayed, the composite is thermally processed in a ventilated dryer at 160 °C for 15 min.

Table 1
Composition of forming mixtures (amount of sapropel[a] 5 % by HS mass) and compaction level.

Designation of specimens	Compaction level, %	HS size, mm	Amount of PPW[a], % by HS mass
S1	60	5/10	15
S2	40	5/10	15
S3	20	5/10	15
S4	60	10/20	15
S5	40	10/20	15
S6	20	10/20	15
S7	60	2.5/5	15
S8	40	2.5/5	15
S9	60	5/10	30
S10	40	5/10	30
S11	60	10/20	30
S12	40	10/20	30
S13	60	2.5/5	30
S14	40	2.5/5	30
S15	60	>20	30
S16	40	>20	30

[a] Amount of sapropel and PPW by dry materials.

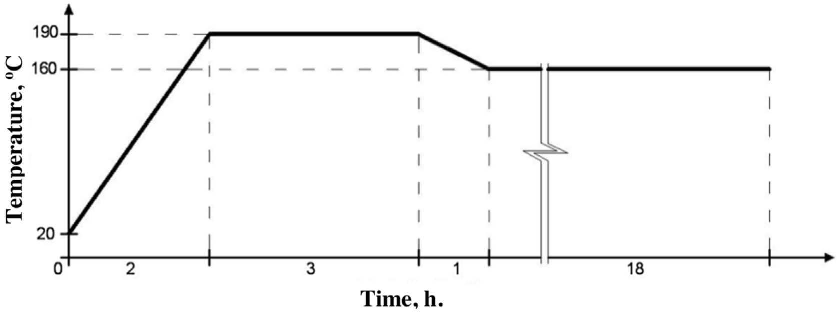

Fig. 1. The thermal treatment of samples.

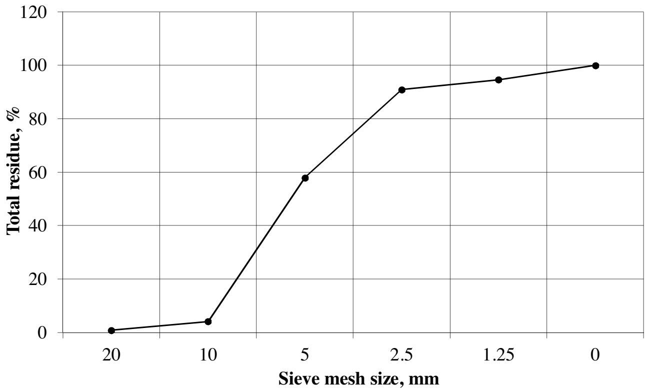

Fig. 2. Granulometry of HS.

1.5. Composition of samples

The previous research (Balčiūnas et al., 2014) has shown that the optimum amount of sapropel in a composite is 5% of HS mass by dry materials. To evaluate the influence of compaction level of forming mixture, HS granulometry and PPW amount on the properties of the composite, the samples indicated in Table 1 are formed.

1.6. Preparation of samples

The HS and sapropel binder have been blended in a non-gravity rotary mixer. Mineral oil has been applied to moulds and the mixture has been laid in three steps. After each step, the mixture has been compacted by a metal bar. The fully filled moulds have been covered by a metal plate, placed into a compressive stand and pressed up to 20%, 40% or 60% decrease in volume. The compressed and fixed forming mixture is thermally processed in a ventilated oven.

The hardening regime of the composite is presented in Fig. 1. The highest hardening temperature of 190 °C is chosen. At this temperature, the hardened sapropel absorbs the least amount of water. The short-term water absorption of sapropel hardened at 110 °C, 150 °C and 190 °C, is approximately 120%, 110% and 70% by mass, respectively. Water absorption decreases with the increase in hardening temperature due to the hydrophobization effect of the melted waxes and bitumen compounds in a sapropel. Higher temperatures than 190 °C cannot be used as the disintegration (burning) process of organic materials begins.

The hardened samples are dried up to a constant mass, and then the thermal conductivity is measured. Afterwards, they are cut into specimens of certain dimensions in order to determine their compressive strength, water vapour diffusion resistance factor, sound absorption coefficient and water absorption. The specimens have been conditioned according to the relevant standards.

1.7. Test methods

The thermal conductivity of the composite and loose HS was determined according to EN 12667 using LaserComp FOX 304 device. Thermal conductivity measurements were performed at an average temperature of 10 °C, while the temperature drop during measurement was of 20 °C. The investigations were performed using the thermal conductivity of dry and air-dry materials. For each composition, 3 specimens are measured.

The compressive stress at 10% deformation was determined according to EN 826 using the computerised equipment "Haunsfield-H10KS" and software "Qmat Professional". The samples had dimensions of (100 × 100 × d) mm, where d is the thickness of a sample, which depends on the compaction level. At the compaction levels of 20%, 40% and 60%, the thicknesses of

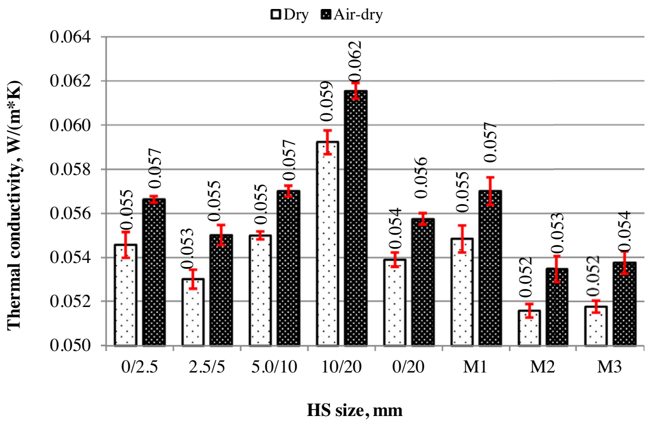

Fig. 3. Thermal conductivity of different HS sizes (M1–10/20–75%, 5/10–25%;M2–10/20–25%, 5/10–75%, M3–10/20–50%, 5/10–50%).

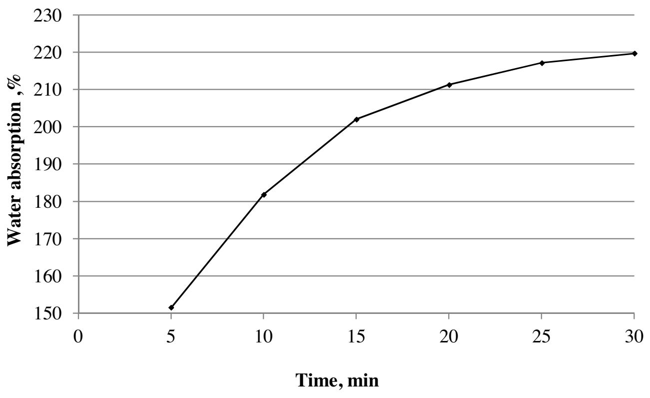

Fig. 4. HS water absorption by mass, %.

samples were 128 mm, 96 mm and 84 mm, respectively. The loading speed was 0.1 d/min. For each composition, 3 specimens were measured.

The water vapour diffusion resistance factor was determined in accordance with the standard EN 12086 (set A). The samples having the dimensions of (100 × 100 × 50) mm were used. For each composition, 3 specimens were measured.

Sound absorption measurements were performed using the standing wave ratio by the impendence tube method. This method enables obtaining the absorption values at a normal sound incidence using small samples. The internal diameter of Kundt's tube used for the measurements was 85 mm, the length – 1000 mm, which corresponds to a frequency range from 150 Hz to 2000 Hz. All procedures described in the ISO 10534-1 were followed. For each composition, 3 specimens were measured.

2. Results and discussion

2.1. HS properties

2.1.1. Granulometry impact on thermal conductivity

The granulometry of unfractionated HS is presented in Fig. 2. The highest amounts of HS sizes are of 5/10 mm (49.1%) and 2.5/5 mm (34.6%).

The thermal conductivity of unfractionated (<20 mm) dry HS (Fig. 3) is 0.054 W/(m K), air-dry – 0.056 W/(m K) (standard deviations of the measurements vary from 0.000153 W/(m K) to 0.00624 W/(m K)). Thermal conductivity is higher for single sizes; only the fine size of 2.5/5 mm has slightly lower thermal conductivity (1.8% and 1.4% for dry and air-dry materials, respectively). The coarse size of 10/20 mm has a noticeably higher thermal conductivity (9.8% and 8.6%, respectively). The coarser particles create larger air gaps in composite, which intensify heat transfer through gas phase. In the case of finer particles, the gaps are smaller; therefore, thermal conductivity by gas (convection) is slower. Fine particles fill the gaps among large particles in the mixtures of coarse and fine HS. The mixture M2 (5/10 mm–75% and 10/20 mm–25%) has the lowest thermal conductivity, the mixture M3 (5/10 mm–50% and 10/20 mm–50%) has only slightly higher thermal conductivity. Thermal conductivity of these mixtures (both dry and air-dry) is by ∼4% lower compared to the unfractionated HS. The mixture M1 with the prevailing coarse size (75% 10/20 mm and 25% 5/10 mm) has thermal conductivity already higher than that of unfractionated HS. Obviously, the influence of HS granulometry is not significant in decreasing the thermal conductivity. Comparing these parameters for dry and air-dry HS, thermal conductivity increases similarly in an air-dry state for both the single sizes and the unfractionated HS (from 3.5% to 3.8%), except for the size of 10/20 mm which shows an increase by 5.1%.

2.1.2. HS water absorption

The rate of water absorption by mass of the unfractionated HS is shown in Figure 4. It can be seen, that water absorption of HS is very intensive and reaches 150% in 5 min (1.5 times higher than its own mass); the absorption rate is 30%/min. From 5 min to 15 min the absorption by mass increases from 150% to 200%, i.e. 6%/min. Water absorption come to an end after 30 min and the final value reaches 220%. High water absorption of the HS is caused by open-cell microstructure. The HS absorption is clearly very high and the hydrophobization of the composite is necessary.

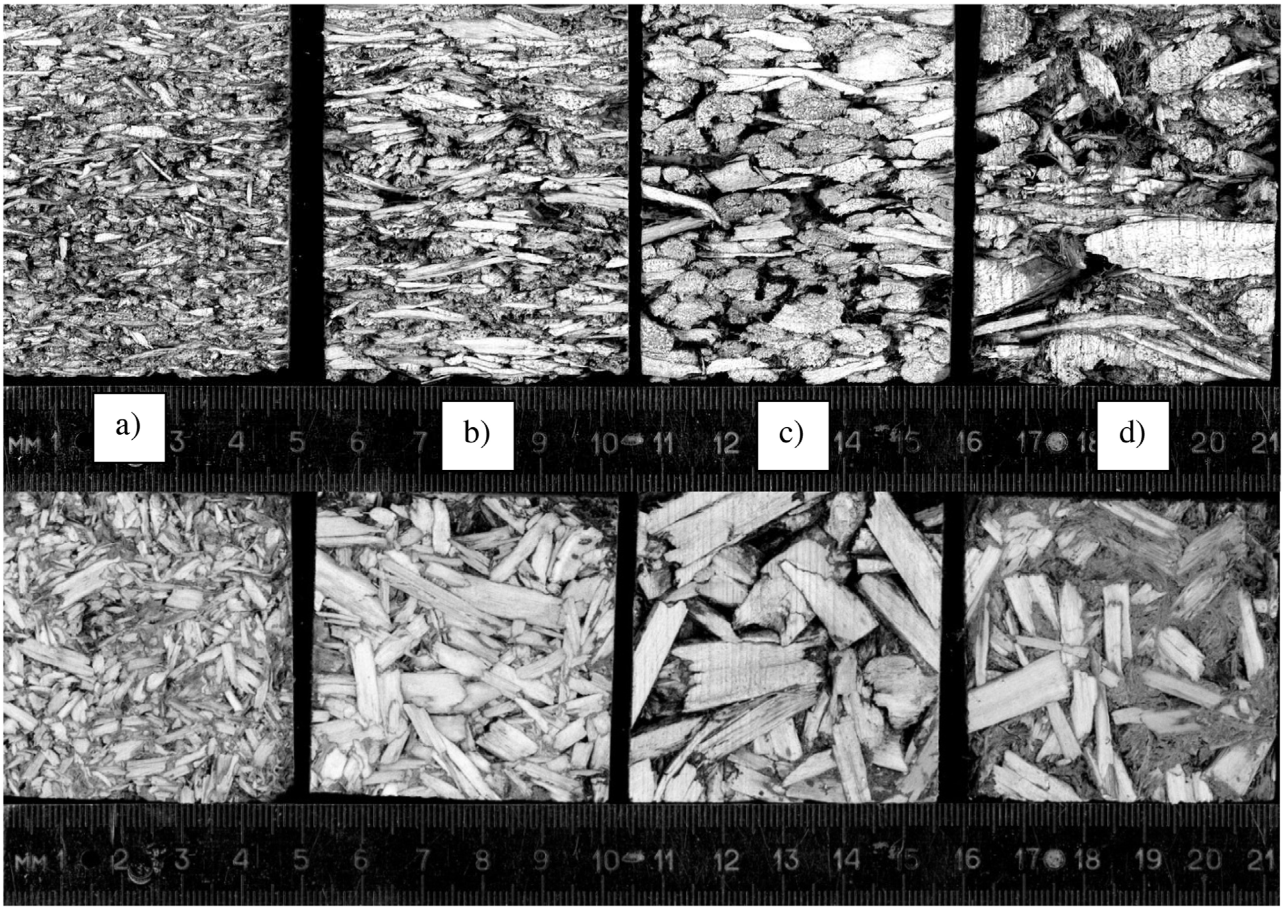

Fig. 5. Macrostructure of the composite: a) – Fr. 2.5/5; b) – Fr. 5/10; c) – Fr. 10/20; d) – Fr. >20 mm.

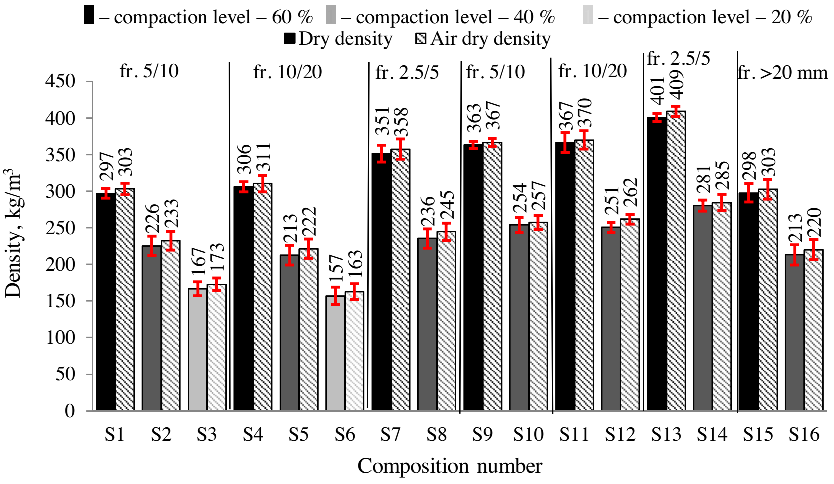

Fig. 6. Density of the composites according to Table 1.

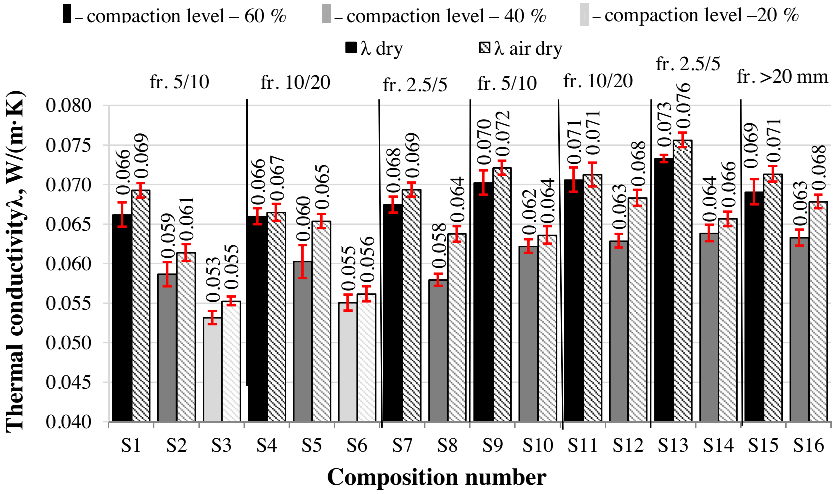

Fig. 7. Compaction level and HS size impact on thermal conductivity of composite.

2.2. *Properties of the hardened HS composite*

Fig. 5 demonstrates the macro- structure of composites with different HS sizes. The macro – structure perpendicular to the forming direction is shown at the top of Fig. 5 and parallel to the forming direction – at the bottom of Fig. 5. It can be observed that HS in the plane parallel to forming direction are orientated horizontally via compaction. In the plane perpendicular to forming direction HS are deployed chaotically and open air cavities are prevailing in the structure of composite. The lowest air cavities are found for composites where the smallest size of HS is used. Size of air cavities determines thermal transfer by convection, i.e.the larger cavities result in higher thermal conductivity of the composite.

2.2.1. *Density*

Fig. 6 presents density values of the dry and air-dry composites prepared according to the parameters given in Table 1. Densities of the dry composites range from 157 kg/m^3 to 401 kg/m^3 (standard deviations of the measurements vary from 5.14 kg/m^3 to 13.8 kg/m^3) and for air-dry composites vary from 163 kg/m^3 to 409 kg/m^3; it depends not only on the compaction level, but also on the HS granulometry and amount of PPW. The samples with HS

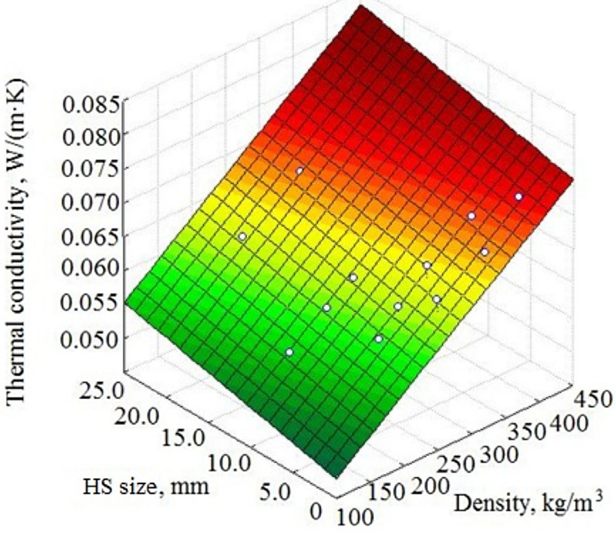

Fig. 8. Thermal conductivity dependence on HS size and density.

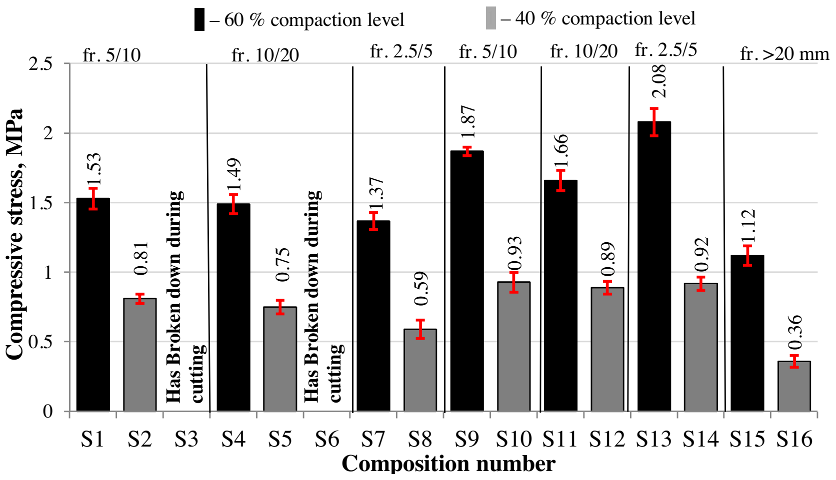

Fig. 9. Impact of compaction level and HS size on composite compressive stress.

size of 2.5/5 mm and larger amount of PPW (30%) have higher density. At the same compaction level and the same amount of PPW, the samples with coarser HS have by 10–20% lower density.

2.2.2. Thermal conductivity

The changes in the values of thermal conductivity at different compaction levels and different HS granulometry are shown in Fig. 7 (standard deviations of the measurements vary from 0.000464 W/(m K) to 0.00208 W/(m K)). One can see, that the thermal conductivity of a composite depends mostly on the compaction level, i.e. density of a composite (Fig. 6). The influence of HS size is quite small. The lowest thermal conductivity is obtained when 20% of compaction level is used, but composites with mentioned compaction level do not match minimum requirements for mechanical properties (specimens have broken down during cutting). Significantly higher thermal conductivity is obtained for composites with the forming mixture compacted 60% by volume. This can be attributed to higher density and larger area of contact zones between HS, thus resulting in a higher heat transfer via solid carcass as well as higher thermal conductivity. Heat transfer by convection is not significant.

On the basis of experimental data, statistical calculations are performed with statistical analysis software Statistica 8.0. The interdependence of thermal conductivity λ, density ρ and HS size Fr (e.g. when size is of 2.5/5 mm, $Fr = 2.5$ mm) is defined and expressed by a multiple regression equation with two parameters and a standard deviation S_r as well as a squared correlation ratio η^2:

$$\lambda = 0.03992 + 0.00008 \cdot \rho + 0.000302 \cdot Fr, \qquad (1)$$

where: $\eta^2 = 0.97$, $S_r = 0.00101$ W/(m K). This demonstrates that the thermal conductivity by 97% depends on the density and the HS size and only by 3% on the other parameters.

This equation is applicable when the dry density of a composite is within the range from 100 kg/m^3 to 450 kg/m^3 and the HS size is within the interval from 2.5 mm to 20 mm. The graphical representation of the thermal conductivity dependency on density and HS size is presented in Fig. 8. In comparison, with hemp-lime composites the thermal insulating properties of hemp-sapropel composite are significantly better. Thermal conductivity of hemp-lime composites varies from 0.542 W/(m K) to 0.078 W/(m K) (Mazhoud et al., 2016; Elfordy et al., 2008), meanwhile for HS and sapropel composites it varies from 0.055 W/(m K) to 0.076 W/(m K). Composite with sapropel binder has lower thermal conductivity because sapropel binder has lower density; therefore, lower heat losses through the solid carcass are obtained.

2.2.3. Compressive stress

The values of compressive stress at 10% deformation are given in Fig. 9. It can be seen, that compressive stress is mainly affected by the compaction level. The highest compressive stress values (up to 2.08 MPa) are for composites with forming mixtures compacted 60% by volume. Standard deviations of the measurements vary from 0.031 MPa to 0.14 MPa. The lowest stress values have been found for composites with 20% of compaction level. Specimens have collapsed during cutting. The amount of reinforcing additive also has a noticeable impact on compressive stress. The values of compressive stress for the composite with 30% of PPW are by 18%–27% higher than for the composite with 15% of PPW. The HS size HS size from 2.5 mm to 20 mm has an inconsiderable impact on compressive stress; only when HS size is >20 mm the values of compressive stress are noticeably lower. The poor mechanical properties of the composite with HS >20 mm are predetermined by the hemp stems particles which are larger than 20 mm in diameter and quite long (approx. 50–100 mm) as this greatly decreases the number and the area of contact zones. Minimum requirements of compressive stress for thermal insulating materials, such as mineral wool or expanded polystyrene (EPS), depend from the application. For

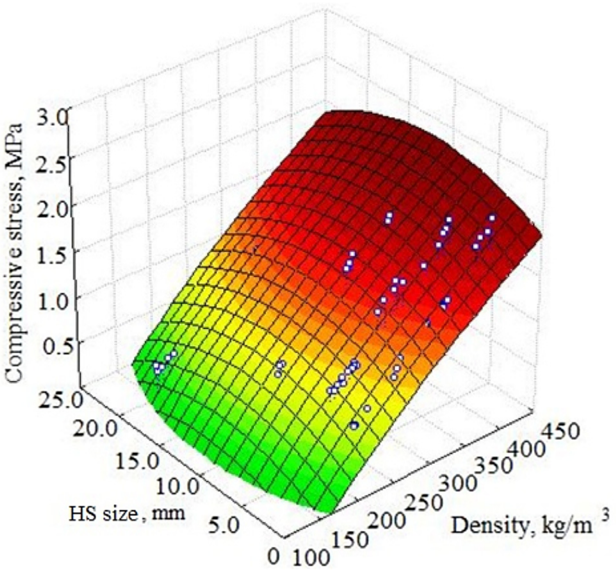

Fig. 10. Compressive stress dependence on HS size and density.

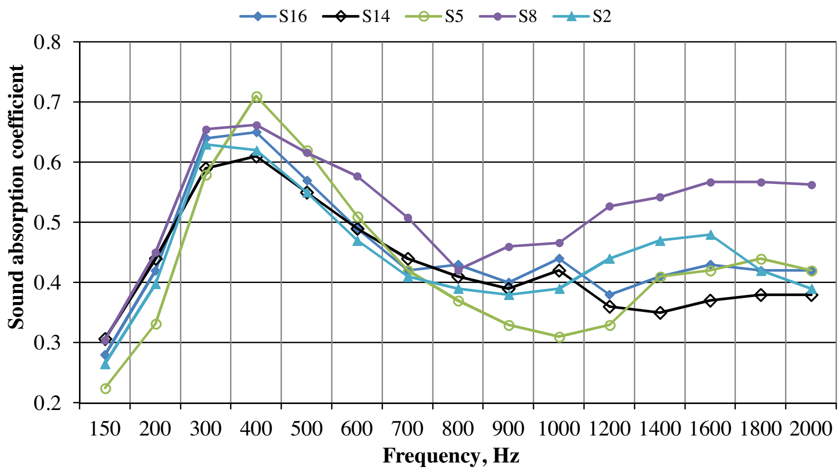

Fig. 11. Sound absorption coefficient of composites.

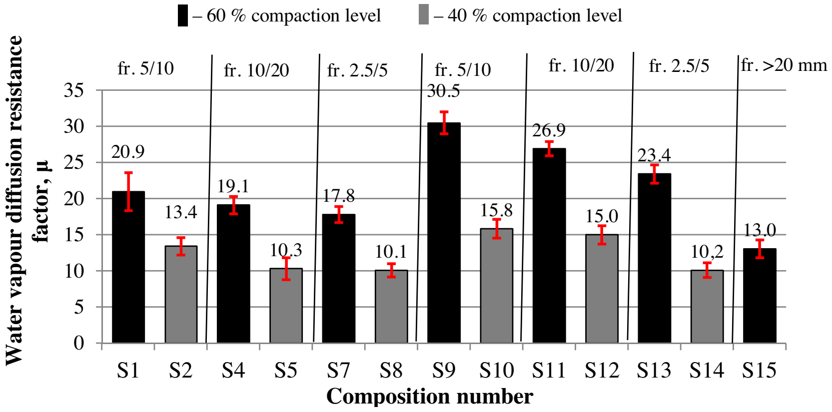

Fig. 12. Water vapour diffusion resistance factor of composites.

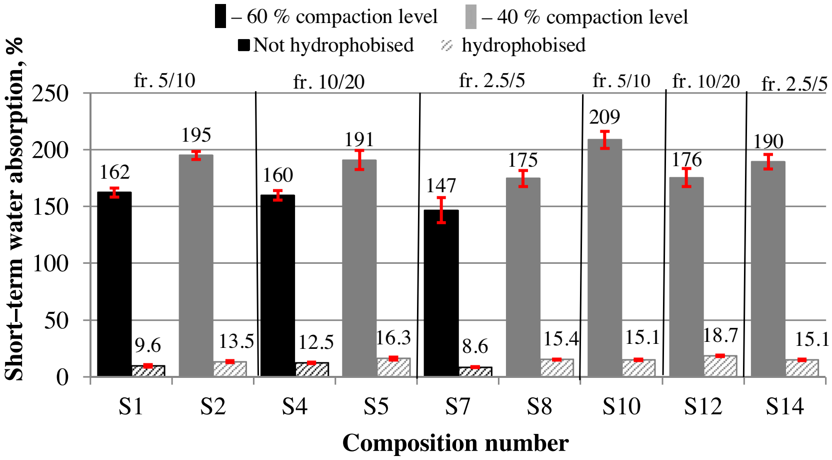

Fig. 13. Short–term water absorption of hydrophobizated and non-hydrophobizated composites.

example, EPS used in wall insulation should have the minimum compressive stress of 70 kPa.

Statistical calculations analogous to the calculations of thermal conductivity are performed. The interdependence of compressive stress at 10% deformation σ_{10}, density ρ and HS size *Fr* is defined and the regression equation derived. It enables prediction of compressive stress of a composite:

$$\sigma_{10} = 2.94 - 0.2296\sqrt{\rho} - 0.0605 \cdot Fr + 0.025 \cdot Fr^2 \qquad (2)$$

where: squared correlation ratio $\eta^2 = 0.91$, standard deviation $S_r = 0.146$ MPa. This shows that the values of compressive stress by 91% depend on the density and HS size and by 9% on the other parameters.

The graphical representation of the compressive stress dependency on density and HS size is given in Fig. 10.

Comparing the results obtained by this research to the results of Latvian scientists (Pleiksnis et al., 2015), it can be stated that thermal processing of the composite with a sapropel binder and the use of reinforcing additive significantly improve strength properties. Latvian scientists research has shown that the compressive stress of composite with density of 196 m^3/kg is 0.148 MPa, contrary to this, the compressive stress of our composite with sapropel binder is significantly higher, i.e. 0.81 MPa, even though the density is only by 24 kg/m^3 higher, i.e. it is 220 kg/m^3 (composite S5).

2.2.4. Sound absorption coefficient

Normal incidence sound absorption coefficient is measured for all composites, except for the composites S3 and S6 (Table 1). The samples of the composites S3 and S6 collapsed due to their low compaction level (20%) and poor mechanical properties. The composites with high compaction level (60%) almost do not demonstrate sound absorption properties. The HS in these composites are well compacted, the surface is smooth. Therefore, sound waves could not enter inside the composite and dissipate; instead they reflect from the surface of a composite. Only the composites with the compaction level of 40% have sound absorption properties, i.e. their surface is porous. It is known that only open pores, which have a continuous channel of air communication with an external surface, ensure good sound absorption properties (Berardi and Iannace, 2015). The obtained results of sound absorption coefficient at various frequencies for the composites with 40% of compaction level are presented in Fig. 11. It can be seen that in the measuring interval from 150 Hz to 2000 Hz, the variation of sound absorption coefficient is of a similar character for all samples. The highest values of the coefficient (0.60–0.72) are obtained in the frequency interval from 350 Hz to 450 Hz. With the further increase in frequency (up to about 850 Hz), a sudden decrease in the values of sound absorption coefficient is noted (to 0.37–0.42). In the subsequent frequency interval (to 2000 Hz), the values of sound absorption coefficient range from 0.31 to 0.48. Except for the composite S8 (HS size of 2.5/5), the values of sound absorption coefficient in the high frequency interval are noticeably higher (0.52–0.56). Comparing with other materials, the sound absorption coefficient at 500 Hz frequency (0.62) is higher than for expanded polystyrene (0.5), wood wool (0.32), coco fibre (0.42), however, it is lower than cellulose (1.0), rock wool (0.91), kenaf (0.74) (Asdrubali, 2006). Sound absorption properties of the hemp shives concrete with lime and cement binder (density varies from 310 kg/m^3 to 420 kg/m^3) are reported by Glé et al., 2011. The sound absorption coefficient of these composites at 500 Hz varies from 0.35 (for cement binder) to 0.45 (for lime binder)é.

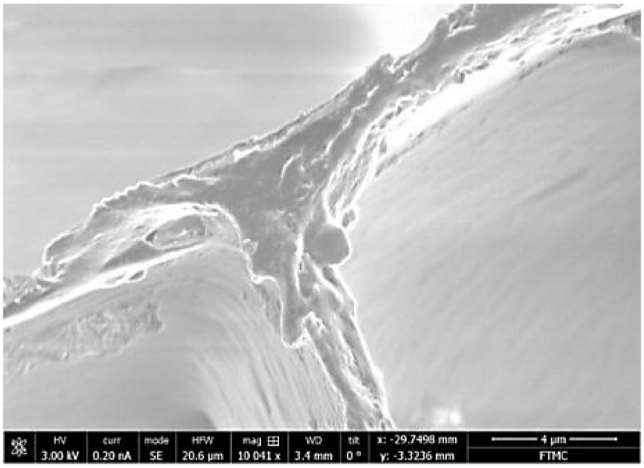

Fig. 14. Hydrophobizating film (magnification ×10000).

2.2.5. Water vapour diffusion resistance factor

Water vapour permeability is an important property for thermal insulating materials. It determines the moisture regime of a partition. Relative vapour resistance of the HS sapropel composites is presented in Fig. 12. Standard deviation of the measurements varies from 0.90 to 2.63. It can be seen, that vapour resistance is mostly dependent on composite compaction, i.e. with the higher density of a composite the vapour resistance increases. In the composite with the lower compaction level, a larger number of gaps appear among HS particles. These gaps are permeable to water vapour. Vapour resistance of the composites with higher amount of PPW (30%) is also higher due to the increased density of the composites (Fig. 6). Comparing vapour resistance of the HS composite with other materials (EN ISO 10456), a conclusion can be made that vapour resistance of the HS composite is close to the vapour resistance of wood fibre slabs.

2.2.6. Short-term water absorption

The short-term water absorption is also an important property of thermal insulating materials. It influences not only the usage possibilities of a material, but also its durability. The water absorption by HS is especially intensive (Fig. 4). The non-hydrophobized HS sapropel composites also demonstrate intensive water absorption and the amount of absorbed water is up to 2 times higher than the mass of the composite itself and in some cases reaches 209% by mass (standard deviations of the measurements when

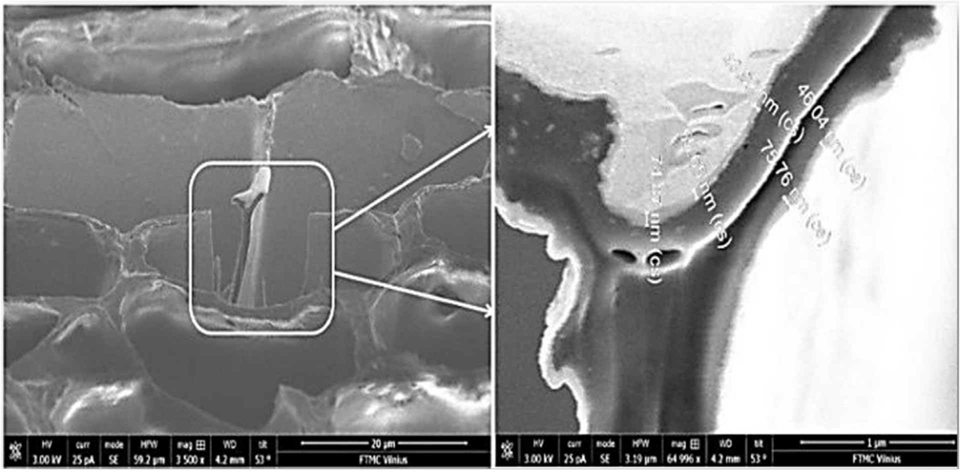

Fig. 15. Hydrophobizating film. a) – magnification ×3500, b) – magnification x65000.

non-hydrophobized composite is tested vary from 3.51% to 11.0%). Investigations have shown that this undesirable property might be easily eliminated by hydrophobization of a composite surface. The short-term water absorption of the hydrophobized and non-hydrophobized composites is presented in Fig. 13. The figure demonstrates that hydrophobization decreases the water absorption in some cases nearly to 17 times, the water absorption after hydrophobization is approximately 8.6%–18.7% (standard deviations of the measurements when hydrophobized composite is tested vary from 0.46% to 1.49%). The more compacted samples (60% of compaction) have lower water absorption, because such specimens have smooth surface which is evenly overlayered by the hydrophobic layer.

2.2.7. Microstructure of a hydrophobic layer

During hydrophobization, the surface of a material is covered by a thin layer of hydrophobic material. Fig. 14 demonstrates HS, covered by a hydrophobizing agent. It can be seen the hydrophobic layer, which smoothly covered the HS surface. The measure of the layer thickness in small samples cut down by an electron flow gun from hydrophobized composite (Fig. 15) shows that the thickness of hydrophobized film ranges from 45 to 75 nm, the average thickness is about 59 nm. It means that the film is very thin and there should not be a noticeable impact on other properties of a composite, such as thermal conductivity, sound absorption, and compressive strength.

3. Conclusions

1 The thermal insulating-acoustic composite having the density within the range of 210 kg/m^3–410 kg/m^3, the thermal conductivity from 0.059 W/(m K) to 0.073 W/(m K) and the compressive stress at 10% deformation within the interval of 0.61 MPa–2.08 MPa might be produced from HS, sapropel binder and reinforcing additive (PPW) when the forming mixture is compacted (40% or 60% by volume) and thermally processed at 190 °C. Although lower compaction level (20%) leads to lighter composites, their mechanical resistance is very poor.

2 Properties of a composite are mainly affected by its density. Density is dependent not only on the compaction level of a forming mixture, but also on the amount of PPW. The granulometry of HS (ranging from 2.5 mm to 20 mm) has much lower influence on the properties of a composite. On the basis of experimental data, statistical calculations are performed and regression equations derived. The regression equations enable prediction of thermal conductivity and compressive stress of a composite, depending on density and HS size.

3 The non-hydrophobized HS composite intensively absorbs water. The amount of absorbed water is up to 2 times higher than the mass of a composite itself. Applying surface hydrophobization, the water absorption decreases more than 10 times and varies from 8.6% to 18.7% by mass. A hydrophobic film is very thin (averagely 59 nm) and does not alter the other properties of a composite.

4 Sound absorption properties are observed only for the samples of lower density with compaction level of 40% by volume. These composites absorb best the waves of 300 Hz–600 Hz frequency. The coefficient of sound absorption exceeds 0.5 for this frequency range. The highest value of sound absorption coefficient is 0.72. The composites compacted at 60% almost do not have sound absorption properties. This is due to the fact, that a smooth surface of a composite with a small amount of pores mainly reflects the sound waves. Additionally, there are almost no cavities that could muffle the sound waves.

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