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PROCESSED STRAW AS EFFECTIVE THERMAL INSULATION FOR BUILDING ENVELOPE CONSTRUCTIONS

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Abstract. The efficiency of thermal insulation materials obtained from renewable resources depends on the possibilities of reducing thermal transfer via solid and gaseous conduction, thermal radiation and, in some cases, convection. The heat transfer mechanism for thermal insulation materials mostly depends on the structure and density of the material used. Efficient thermal insulation materials consist of a gaseous phase and a solid skeleton. Gas content in such materials can take more than 99% of material by volume. In this case, thermal transfer via solid conductivity is negligible.

The current work analyses the possibilities of reducing heat transfer in the straw of a varying structure. For conducting experiments, barley straw was used. To evaluate the impact of straw stalk orientation in a specimen on thermal conductivity, strongly horizontally and vertically oriented specimens of straw stalks were prepared. To reduce heat transfer via gaseous conduction and convection in large cavities in straw stalks and between stalks, barley straw were chopped and defibered. In order to decrease heat transfer via radiation after thermal conductivity measurements, mechanically processed straw were coated with infrared absorbers. Due to thermal conductivity measurements of chopped and defibered straw, an optimal amount of infrared absorbers were determined.

Keywords: thermal insulation, renewable resources, barley straw, straw wool, thermal conductivity, infrared absorbers, building envelope constructions.

1. Introduction

Currently, the global market offers a wide choice of thermal insulation materials for building envelopes. The latest thermal insulation products such as vacuum insulation and gas-filled panels, aerogels, phase change materials (Jelle 2011) or ecological thermal insulation, including fibreboards, loose fill insulation or panels from different plants or their tails (Kymalainen, Sjoberg 2008; Zach *et al.* 2012; Pinto *et al.* 2011) takes a part of this market.

For a period of the last 20 years, cellulose based plant fibres have gained importance as raw material for thermal insulation (Vėjelienė *et al.* 2011). Ecological thermal insulation from local renewable resources is the most common thermal insulation. In addition to the environmental factor, such criteria as recyclability, the renewal of raw materials and low energy production costs have gained considerable importance (Marks 2005; Grmela *et al.* 2010). For producing ecological thermal insulation, a very wide assortment of plants – barley, triticale, rye, wheat and rice straw, flax, hemp and nettle fibres or shives, reed, cattail *et al.* plant stalks – are used (Halvarsson *et al.* 2009; Gailius, Vėjelis 2010; Murphy *et al.* 1997; Sain, Panthapulakkal 2006).

Each year, fertile soil in some of the crop farms composes large quantities of waste straw (up to 6t/ha and more) commonly used as a fertilizer. Mineralization and turning them into organic compounds in soil, under the circumstances of large quantities of cereals in crop structure, are problematic (Arlauskienė *et al.* 2009; Moran *et al.* 2005).

Throughout history, people have built homes using straw, grass or reed. These materials have been used due to their reliability and ease to be obtained. Some European houses built of straw or reeds have been countered two hundred years. People in the United States have also turned to straw houses, particularly after the hay/straw bale entered the common usage in the 1890s. For example, homesteaders in the area of north-western Nebraska "Sand hills" turned to baled-hay construction for the reason of a shortage of trees for lumber. Bale constructions were used for homes, farm buildings, churches, schools, offices and grocery stores (Marks 2005).

Straw can be used in bulk, lose ground, pressed and tied up as a component of other building material or incorporated into the panels. The easiest way of the use of local renewable resources are milling them and use as lightweight aggregate in different blocks. For manufacturing blocks, virtually, the particles of all the plant can be used. For manufacturing block chaff, sawdust, chopped wood and chopped straw are used. In such blocks as matrix lime, cement, gypsum, clay and the mixtures of these substances are used (Kazragis 2005; Kazragis, Gailius 2006).

For manufacturing thermal insulation materials from renewable resources, available thermal conductivity is approximately 0.041 W/(m·K) and even lower (Beck *et al.* 2003). The thermal conductivity of materials under realistic conditions may increase. This is due to different conditions for preparing materials in the laboratory and installation in building construction. Straw in the laboratory are usually tested in bulk and their density ranges from 40 to 60 kg/m^3. Meanwhile, straw in the constructions are compressed to 90–110 kg/m^3. Such density in the structure is required so that to ensure straw will not settle and maintain short-term and long-term loads. Investigations into thermal resistance to the climatic chamber (Stone 2003) have shown that the obtained results of various researchers were very different – thermal resistance of 2.5 cm thickness varied from 0.176 m^2·K/W to 0.555 m^2 K/W or recalculated to thermal conductivity – from 0.041 to 0.140 W/(m·K).

The aim of the current study is to determine the impact of oriented straw stalks on the thermal conductivity of a specimen, to reduce heat transfer in straw by mechanical processing and coating with infrared absorbers, to define the dependence of different straw orientation in specimens and straw densities of various structure on thermal conductivity according to the measurements of thermal conductivity and to discover an optimal amount of infrared absorbers for chopped and defibered straw.

2. Experimental

For vertically and horizontally oriented tests, chopped and defibered barley straw stalks were used. Vertically and horizontally oriented straw were carefully prepared from small straw bales while they were strongly oriented in specimen. The prepared straw specimens are shown in Fig. 1.

a) b) c) d)

Fig. 1. Straw specimens prepared for measuring thermal conductivity: a) vertically oriented, b) horizontally oriented, c) chopped, d) defibered

Chopped straw were prepared by a rotary mill. Loose straw were filled into earlier prepared forms with the dimensions of 500×500 mm.

The preparation of defibered straw was more difficult. First, straw were kept in water for the fixed time. Next, they were put on the metal mesh for the fixed time on purpose of the even distribution of water in straw and the removal of water excess from straw. Such regime was required because dry straw in the mill were pulverized in a few minutes.

Very wet straw in the mill turned into lump. Properly prepared straw were well defibered and about 95% of all content became straw fibre, which we entitled straw wool.

One part of horizontally oriented, chopped and defibered straw specimens were coated with infrared absorbers.

For this purpose, graphite particles were used. Flax oil was used as binder.

Before measuring straw, specimens were loaded under 5 different loads – 50, 200, 500, 1000 and 2500 Pa. Such loading was used for evaluating the dependence of thermal conductivity on straw density. For thermal conductivity, the measurements of 5 specimens of every structure of straw for every loading were prepared.

A test on thermal conductivity was carried out applying guarded hot plate apparatus λ-Meter EP 500 (Fig. 2) with additional protective heating rings and a cooling ring according to (ISO 8302). The measurements of thermal conductivity were carried out at a mean temperature of 10 °C and difference in temperature through the specimen of 10 °C. All specimens were conditioned under constant climate conditions (23±2) °C and (50±5)%.

Fig. 2. Apparatus λ-Meter EP-500 for testing thermal conductivity

For microstructure analysis of straw mechanically processed and coated with infrared absorbers, a scanning microscope EVO 50 EP was used.

3. Test results and discussion

Test results of vertically oriented straw are presented in Fig. 3. Test results show that thermal conductivity depends on straw density. However, changes in thermal conductivity in all ranges of densities are very small. The biggest difference between experimental values of thermal conductivity makes only 3%. The lowest thermal conductivity of vertically oriented straw in the range of densities from 90 kg/m^3 to 115 kg/m^3 is observed. Thermal conductivities decrease practically in all ranges of densities, including specimen densification. Higher thermal conductivity in a lower range of densities is observed due to an open structure of the formed specimens (Fig. 4) and a huge impact of heat

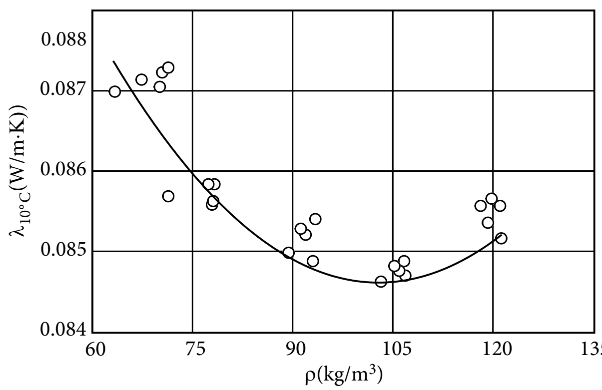

Fig. 3. The dependence of thermal conductivity on the density of vertically oriented straw

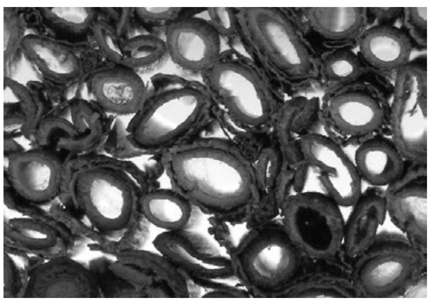

Fig. 4. View of specimens having a parallel to heat flow oriented straw

transfer due to the conduction of gas and probably of convection. In the range of densities from 90 kg/m^3 to 115 kg/m^3, the curve of thermal conductivity changes a direction, i.e. the values of thermal conductivity start increasing. In this case, thermal conductivity increases due to the conduction of solid material.

Such increase is determined by the densification of straw stalk walls and stronger contact zones between them.

To establish the relationship between horizontally oriented straw and their density, experimental data were approximated using regression equation

$$\lambda = 0{,}09637 - 0{,}00146 \cdot \rho + 0{,}0000107 \cdot \rho^2, \quad (1)$$

with standard deviation S_r = 0.003174, W/(m·K) (i.e. an absolute value of a standard deviation of experimental data from the empirical regression line, constant for all its section), which was determined by the formula:

$$S_x = \sqrt{\frac{\sum_{i=1}^{n}\left(\lambda_i - \bar{\lambda}\right)^2}{n-1}}, \quad (2)$$

where λ_i is an experimental value of thermal conductivity; $\bar{\lambda}_i$ is the same value based on empirical relationship (1); n is the number of experimental data.

Test results of horizontally oriented straw presented in Fig. 5 show that the dependence of thermal conductivity on straw density is very close. Thermal conductivity in the range of density from 75 kg/m^3 to 120 kg/m^3 increase more than 1.5 times. The lowest thermal conductivity of horizontally oriented straw is in the range of density from 65 kg/m^3 to 85 kg/m^3. In other cases, i.e. when the density of straw specimens is lower or higher, thermal conductivity increases. In the area of low density (50÷65 kg/m^3) between straw stalks, air spaces are large enough. Therefore, air molecules move intensively and heat transfer increases due to the conduction of gas, whereas in the area of high density (85÷120 kg/m^3), heat transfer increases as a result of conduction of solids. In this case, straw stalks are heavily compressed, contacts between a solid skeleton are very strong and intensive heat transfer resulting from solid conductivity is eligible.

Based on the obtained experimental data, the relationship of vertically oriented straw between thermal conductivity and material density may be approximated by regression equation

$$\lambda = 0{,}10312 - 0{,}00036 \cdot \rho + 0{,}0000175 \cdot \rho^2, \quad (3)$$

with standard deviation S_r = 0.000361.

With the aim of reducing heat transfer due to the conduction of gas, straw were mechanically chopped. Chopped straw fill better air spaces, contacts between straw stalks reduce and these contacts are not continuous. Fig. 6 (points ◆) presents the results of measuring the thermal conductivity of chopped straw. The analysis of tested results shows a lower thermal conductivity of chopped straw than that of the horizontally oriented ones. Such thermal conductivity is similar to effective thermal insulation, i.e. conductivity is much the same as effective thermal insulation i.e. mineral wool, expanded polystyrene.

Fig. 6 (points △) shows the measurements of the thermal conductivity of defibered straw. Thermal conductivity values of defibered straw are lower in the full range of densities than those in the chopped ones. The structure of defibered straw is similar to mineral wool. Very thin fibres of straw contact each other only per thickness of fibre. This means that heat transfer due to solid conduction decreases. Thin and short fibres fill air spaces better than chopped straw. Small pores are

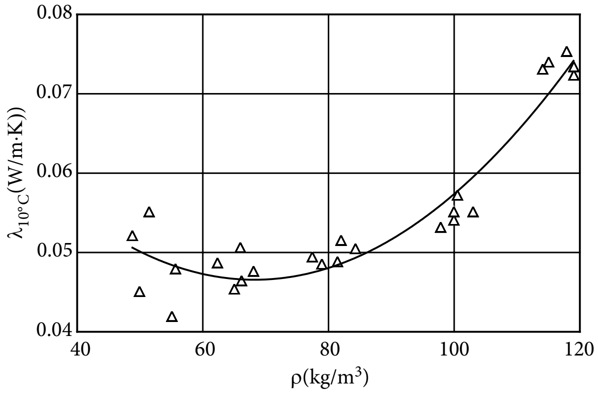

Fig. 5. The dependence of thermal conductivity on the density of horizontally oriented straw

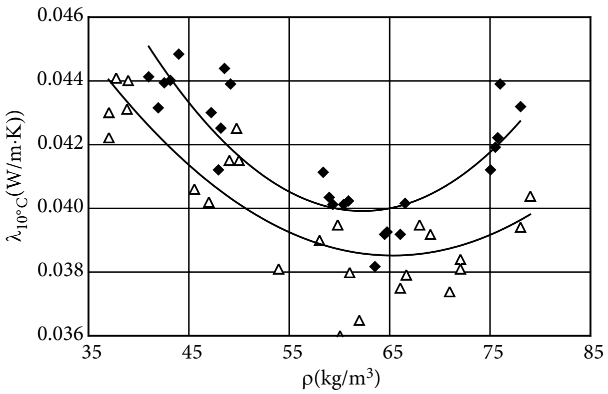

Fig. 6. The dependence of thermal conductivity on the density of: ◆ – chopped straw, △ – defibered straw

formed between thin fibres where air molecules move very slowly and heat transfer reduces because of conduction.

Moreover, the structure of straw changes very significantly during mechanical processing. A general view of defibered straw is presented in Fig. 7a. After the process of defiberation, inner (Fig. 7b) and outer (Fig. 7c) layers of straw stalks are separated. Thin fibres are formed from the outer layer. In such a way, a solid surface from the inner layer is removed and the remaining layer stays more porous with small open pores.

From a thermal conductivity viewpoint, a solid frame is destroyed and heat transfer by conduction direct trough straw stalk is reduced.

a)

b)

c)

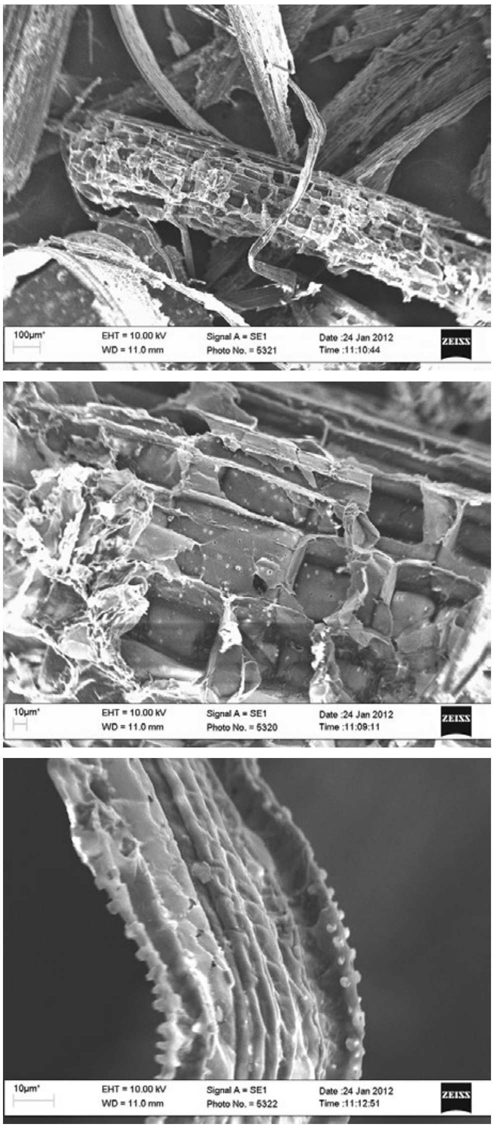

Fig. 7. View of defibered straw: a) a general view of straw fibre (200×), b) the inside part of straw stalk (1 000×), c) an outer part of straw stalk (3 000×)

The dependences of the thermal conductivity of chopped straw (4) and defibered straw (5) on their density were approximated by using regression equations

$$\lambda = 0,08414 - 0,00142 \cdot \rho_s + 0,0000114 \cdot \rho_s^2, \quad (4)$$

with standard deviation $S_r = 0.001082$, and

$$\lambda = 0,06791 - 0,00090 \cdot \rho_p + 0,00000689 \cdot \rho_p^2, \quad (5)$$

with standard deviation $S_r = 0.001217$.

After the measurements of thermal conductivity, chopped and defibered straw were coated with graphite used as an infrared absorber to reduce heat transfer due to radiation. Chopped and defiberd straw were coated with a different amount of graphite particles. The results of measuring the thermal conductivity of coated straw are presented in Figs. 8a and 8b.

Thermal conductivity values of the same straw density were different and have changed depending on the amount of graphite particles. For chopped straw 5% by mass of infrared absorbers of the dry straw weight

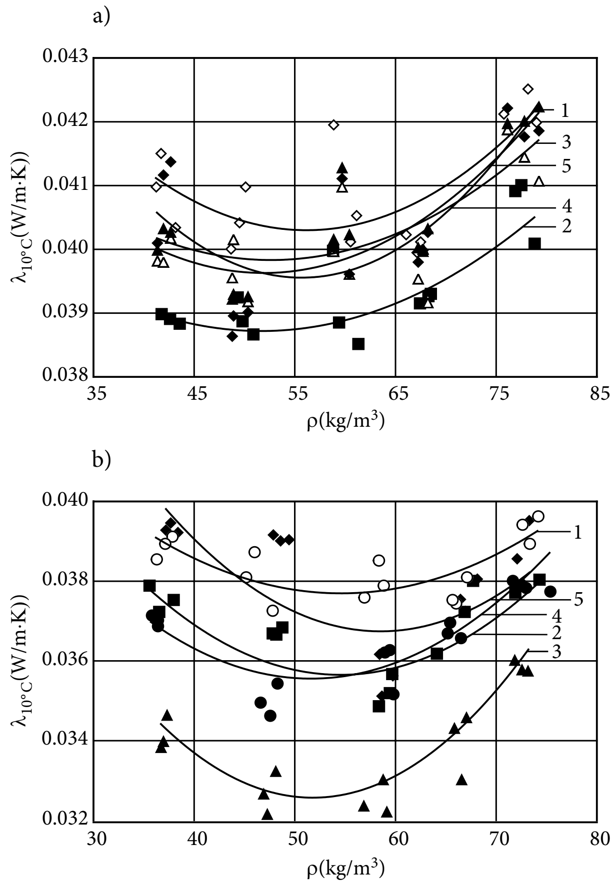

Fig. 8. The dependence of the thermal conductivity of mechanically processed straw on graphite content: a) chopped straw when graphite content by mass makes 1 – 3%, 2 – 5%, 3 – 7%, 4 – 10%, 5 – 20%, b) defibered straw when graphite content by mass makes 1 – 3%, 2 – 5%, 3 – 7%, 4 – 10%, 5 – 20%

were used for gaining the lowest thermal conductivity. Although defibered straw having the same content of infrared absorbers show lower thermal conductivity than that in the chopped straw, however, a decrease in thermal conductivity of 7% can be also observed. Such situation indicates that the content of the efficiency of infrared absorbers depends mostly on the surface area of the prepared materials.

A higher content of graphite increases thermal conductivity in all density ranges. An increase in thermal conductivity is related to an overall increase in material density and closer contact zones between straw particles due to the infrared absorber.

Such fact confirms microstructure analysis presented in Fig. 9. On the chopped straw walls with 3% of infrared absorbers, white spots are observed, which means a deficit of graphite. When 5% of infrared absorbers are used, the surface of straw walls is evenly coated with graphite. Visible excess of infrared absorbers is observed when 10% of infrared absorbers are applied. In this case, the collection of graphite on the walls of straw composes. For chopped straw coated with an optimal content of 5% of graphite particles and defibered straw with 7%, dependences (6) and (7) of thermal conductivity on material density were approximated using regression equations

$$\lambda = 0{,}04518 - 0{,}00025 \cdot \rho_s + 0{,}00000242 \cdot \rho_s^2, \quad (6)$$

with standard deviation S_r = 0.000471, and

$$\lambda = 0{,}05422 - 0{,}00084 \cdot \rho_p + 0{,}00000811 \cdot \rho_p^2, \quad (7)$$

with standard deviation S_r = 0.000532.

The publications of other researches do not present any information about the thermal conductivity of chopped and defibered straw coated with infrared absorbers. Moreover, a lack of information about strongly horizontally or vertically oriented straw can be noticed. The experimental results of other researches on straw bales show that the obtained results vary from 0.041 W/(m·K) to 0.140 W/(m·K) (Beck *et al.* 2003). The difference between these results is related to several reasons. First, to determine the thermal conductivity of thermal insulation material with large thickness is difficult due to a lack of facilities or measurement accuracy; second, preparing a thin specimen from straw is very complicated, and therefore the accuracy of measurement reduces. Every time, prepared straw bales change vertical and horizontal components

a)
b)
c)

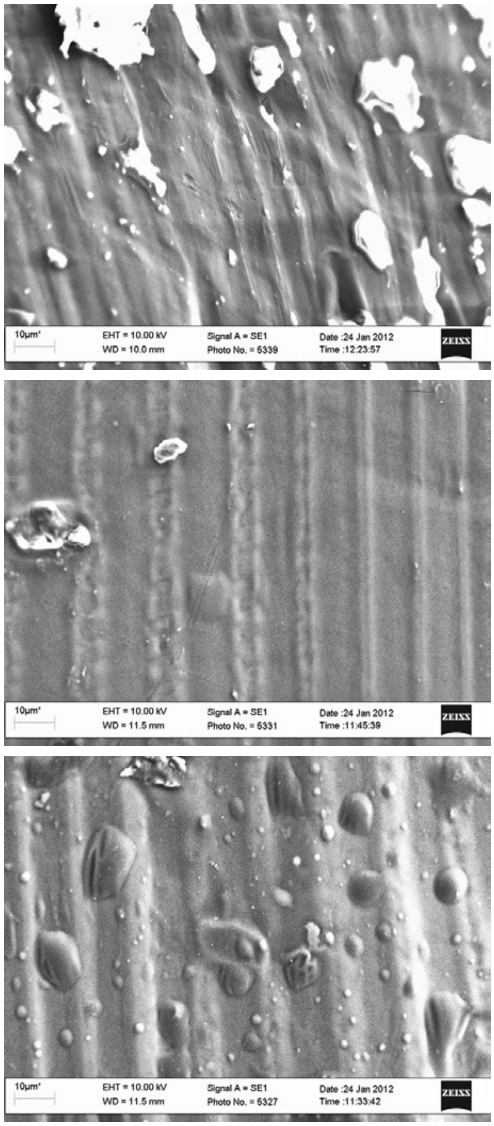

Fig. 9. View of chopped straw coated with a different content of infrared absorbers: a) 3%, b) 5%, c) 10%

in straw content, their compression ratio and density. Another reason is changes in the content of moisture in straw. Thermal conductivity and straw-making features depend on the content of moisture in straw. In the specimen formation of very dry straw, straw stalks begin to break, and in the formation of very wet ones – straw stalks crumple and due to this overall density of the straw specimen increases.

4. Conclusions

1. The thermal conductivity of straw mostly depends on the orientation of straw stalks in the specimen matrix. The highest thermal conductivity can be observed in vertically oriented straw perpendicularly

to the heat flow. The lowest thermal conductivity value of vertically and horizontally oriented straw differs about 1.8 times.

2. The paper proposes the possibility of reducing heat transfer in straw by mechanical processing. For instance, heat transfer can be reduced due to the conductivity of solid and gases. The largest decrease in thermal conductivity observed in chopped straw is about 19% and in defibered straw – about 22%, compare with horizontally oriented straw.
3. The thermal conductivity of chopped straw depends on the content of graphite and the efficiency of additives depends on the density of material. The lowest thermal conductivity of chopped straw can be noticed when the content of graphite makes 5% of a dry weight of material. A higher content of graphite increases the thermal conductivity of chopped straw due to an increase in density and better contact zones between straw particles. This is the reason why heat transfer resulting from conductivity through a solid skeleton of material increases. In the case of defibered straw rather than of chopped straw, gaining a higher content of the graphite of the lowest thermal conductivity is necessary. This is caused by a higher specific surface of material necessary to be coated by graphite.
4. When materials are coated with infrared absorbers, thermal conductivity may be reduced by more than 20%. The impact of infrared absorbers depends on the applied method, the content of infrared absorbers and an even structure of material. The most thermal conductivity is reduced in the range of lower density and fine porous material which has the highest specific surface. Heat transfer of material increases when the content of infrared absorbers is too high (defibered straw >7%, chopped straw >5%).
5. Mechanical processing of straw changes macrostructure in the case of both – chopping and defibering. The spaces between straw are reduced and there are no voids inside the straw stalk. Moreover, microstructure is changed while straw are defibered. During this process, the outer and inner parts of straw stalks are separated. A denser outer part of straw stalk is divided into smaller strips with a thickness of 10÷20 μm and a width of 10÷40 μm. Thanks to smal strips smaller voids in the formed specimens are created and, at the same time, heat transfer due to conductivity through the solid skeleton of material is reduced.

References

Arlauskienė, A.; Maikštėnienė, S.; Šlepetienė, A. 2009. The effect of catch crops and straw on spring barley nitrogen nutrition and soil humus composition, *Žemdirbystė* 96: 53–70 (in Lithuanian).

Beck, A.; Heinemann, U.; Reidinger, M.; Fricke, J. 2003. Thermal transport in straw insulation, *Journal of Thermal Envelopes and Building Science* 27: 227–234.

Gailius, A.; Vėjelis, S. 2010. *Thermal Insulating Materials and Their Products*. Vilnius: Technika. 170 p. (in Lithuanian).

Grmela, D.; Hamšik, P.; Čuprova, D. 2010. Thermal and moisture transmittance in strawbale structures, in *International Scientific Conference*. Krtiny, Chech Republic, 1–6.

Halvarsson, S.; Edlung, H.; Norgren, M. 2009. Manufacture of non-resin wheat straw fibreboards, *Industrial Crops and Products* 29: 437–445. http://dx.doi.org/10.1016/j.indcrop.2008.08.007

Jelle, B. P. 2011. Traditional, state-of-the-art and future thermal building insulation materials and solutions – properties, requirements and possibilities, *Energy and Buildings* 43: 2549–2563. http://dx.doi.org/10.1016/j.enbuild.2011.05.015

Kazragis, A. 2005. Minimization of atmosphere pollution by utilizing cellulose waste, *Journal of Environmental Engineering and Landscape Management* 13(2): 81–90.

Kazragis, A.; Gailius, A. 2006. *Composite Materials and Product Containing Natural Organic Aggregates*. Vilnius: Technika (in Lithuanian).

Kymalainen, H. R.; Sjoberg, A. M. 2008. Flax and hemp fibres as raw materials for thermal insulations, *Building and Environment* 43: 1261–1269. http://dx.doi.org/10.1016/j.buildenv.2007.03.006

Marks, R. L. 2005. *Straw-Bale as a Veble, Cost Effective, and Sustainable Building Material for Use in Southeast Ohio*. College of Arts and Sciences of Ohio University.

Moran, K. K.; Six, J.; Horwath, W. R. 2005. Role of mineral nitrogen in residue decomposition and stale soil organic matter formation, *Soil Sciences Society of America Journal* 69: 1730–1736. http://dx.doi.org/10.2136/sssaj2004.0301

Murphy, D. P. L.; Behring, H.; Wieland, H. 1997. The use of flax and hemp materials for insulating, in *Processing of Flax and Other Bast Plants Symposium*. Poznan, Poland, 30 September–1 October, 79–84.

Pinto, J.; Paiva, A.; Varum, H.; Costa, A.; Cruz, D.; Pereira, S. 2011. Corn's cob as apotencial ecological thermal insulation material, *Energy and Buildings* 43: 1985–1990. http://dx.doi.org/10.1016/j.enbuild.2011.04.004

Sain, M.; Panthapulakkal, S. 2006. Bioprocess preparation of wheat straw fibers and their characterization, *Industrial Crops and Products* 23: 1–8. http://dx.doi.org/10.1016/j.indcrop.2005.01.006

Stone, N. 2003. Thermal performance of straw bale wall systems, in *Ecological Building Network (EBNet)*.

Vėjelienė, J.; Gailius, A.; Vėjelis, S.; Vaitkus, S.; Balčiūnas, G. 2011. Evaluation of structure influence on thermal conductivity on thermal insulating materials from renewable resources, *Materials Science (Medžiagotyra)* 17: 208–212.

Zach, J.; Korjenic, A.; Petranic, V.; Hroudova, J.; Bednar, T. 2012. Performance evaluation and research of alternative thermal insulations based on sheep wool, *Energy and Buildings* 49: 246–253. http://dx.doi.org/10.1016/j.enbuild.2012.02.014

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