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Thermal insulating plates produced on the basis of vegetable agricultural waste

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ABSTRACT

The results of comparative tests of thermal insulating materials on the basis of various agricultural wastes are presented. Rye straw, barley straw, wheat straw, oats straw, rice straw, flax boon and rice husk were used in the experimental program along with three types of binders (liquid glass, emulsion of PVA and latex). Plates prepared with rye straw and flax boon fibers and liquid glass as a binder have the best physical and mechanical characteristics due to the formation of the optimal composite structure of the material from two fibers of different sizes and shapes. The electronic microscopy of rye and flax stems made it possible to establish the presence of outer and inner parts in the structure, which affect the thermal and strength characteristics. Results show that plates made from rye straw and flax boon have lower moisture absorption unlike the rye straw based ones. The results of full-scale tests with a ventilated thermal insulation system confirm the effective operation of rye straw and flax boon plates. The testing program carried out indicates the possibility of using an environmentally friendly straw-flax boon plates for thermal insulating buildings in the cold period and thereby reducing carbon dioxide emissions into the atmosphere.

1. Introduction

Besides thermal properties, sound insulation, resistance to fire, mechanical strength, water vapor permeability and impact on the environment and on human health are relevant properties of thermal insulating materials. Currently, there exist no single insulation material or solution capable of fulfilling all the requirements with respect to the most crucial properties [1].

Raising environmental and public health awareness leads to the development of new insulation materials. Significant potential to improve their overall performance do exists, namely in terms of environmental impact [2].

Building insulation is commonly realized using materials obtained from petrochemicals (mainly polystyrene) or from natural sources processed with high energy consumptions (glass and rock wools). On the other hand, sustainable materials represent an alternative for thermal and sound insulation in buildings, which can be divided into natural materials (such as cotton, hemp, wool, flax, clay, etc.) and recycled materials (such as rubber, plastic, cellulose, carpet, etc.). Natural materials, such as cellulose flocks, cotton or straw, show very low values of embodied energy, while expanded polyethylene or polyurethane exhibit the highest values. There are also some natural materials whose embodied energy is as high as that of synthesized materials [3]. As an example, Pargana et al. [4] showed that expanded cork agglomerate has not lower environmental impact than extruded and expanded polystyrene, and polyurethane. Substitution of conventional thermal and sound insulating materials with some recycled materials has significant effects on the impact of all the various phases of the life of the building (construction, operation, end of life) [3]. Recycled PET showed good environmental performance [5], whereas recycled textile and paper have large energy consumptions [6]. Buratti el al. [7] did the economic assessment of a panel made of wool scraps and waste paper concluding that this solution allows to be cost saving compared with the extruded polystyrene and glass wool.

Natural materials have raised the interest of the scientific community, which is strongly present on research published in the last years, mainly focusing on hemp, straw, flax, wood, coconut, corn and sunflower [8]. The agro-residues can have an interesting role because their use allows the revaluation of agricultural wastes, whose disposal is another serious issue [9].

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Some works showed the potential of environmental viability of agro-residue products for insulation applications. Hemp is one example which has lower global warming potential over recycled polyethylene terephthalate, textile and rock wool [10]. Pennacchio et al. [11] showed that sheep wool and hemp insulation panels have the lower non-renewable energy demand than conventional materials, such as extruded polystyrene foam and glass wool. The main strength in the use of hemp-based materials comes from the production phase because of the "green" origin of these materials, mainly associated with the carbon sequestration during plantation growth. Industrial hemp products, as with most of the renewable raw materials available nowadays, generally score better than conventional materials with regard to the use of fossil fuel and to the emission of Greenhouse Gases [12]. Another example is the life cycle analysis performed by Buratti et al. [13] that showed the best environmental performance for the production of rice husk panels compared with the ones of panels composed by other recycled materials (cork scraps, end-life tires, waste paper, textile fiber mats, wool fiber scraps).

Since most unconventional thermal insulation materials are only at a prototypal stage or at an early stage of commercialization, few information about their environmental impact are currently available. An important requirement influencing the sustainability of these insulators is related to the availability of its components since the use of local materials lead to a reduction of economic and environmental impacts. Using these unconventional materials can reduce the use of oil based and not renewable sources [5].

The main disadvantages of the thermal insulation based on natural materials, which very often precludes their use in thermal insulation systems structures, are high water absorption and poor response to fire [14]. Palumbo et al. [15] evaluated the hygrothermal behavior of six different bio-based insulation materials (hemp lime, hemp fiber, wood wool and wood fiber, straw-starch, and corn pith-alginate), concluding that the choice of the kind of bio-based material may have implications on the overall building performance. Another consideration is the need to protect natural materials against biological attacks (e.g. against fungi and parasites). Nevertheless, the negative properties of materials based on natural fibers can be largely modified by chemical treatment of fibers [14].

Vegetable fibers are finding increasing applications in the construction industry due to their economic, energy and environmental sustainability [16]. When processing agricultural products, significant raw materials (vegetable waste) are generated for the manufacture of thermal insulating materials, and these agro-wastes have shown the potential to develop energy efficient and cost effective sustainable construction materials along with enhanced thermomechanical behaviour [17].

In warm regions a large amount of vegetable waste remains after processing rice and cotton. Technologies of manufacturing thermal insulating plates from rice husks are developed [13], as well as for rice straws [18]. It is also possible to produce thermal insulating plates from cotton stalk fibers [19] and cotton stems with addition of up to 10% of wood chips [20]. Investigations on the use of whole and chopped sunflower seeds in the production of a plate insulation were carried out [21,22]. Flax and hemp are suitable for insulation due to their thermal properties and some ecological features, i.e., biodegradability [23,24]. Pressed thermal insulating plates from mechanically and chemically processed flax boon have been produced in Russia from the beginning of the last century [25]. In Germany, the technology of obtaining thermal insulation material STEICO based on straw of hemp and sawdust was patented [26]. Bamboo fibers can also be used as building insulation materials [27]. For the insulation of buildings in England, France, Sweden and other countries of Western Europe, Stramit plates were used, which were obtained from straw of grain crops by hot pressing and covered with cardboard on both sides [28]. This technology is taken as a basis for the production of modern sandwich panels with aggregate made from straw cereals.

There are undoubtedly strong reasons to believe that agricultural straws are promising in a thermal insulating perspective [29]. The objective of the experimental work carried out was to analyse the application of various types of agricultural waste to the manufacture of thermal insulating panels. Various kinds of fibers such as agricultural straws, flax boon and rice husk, were selected to the present study. In addition, the use liquid glass as a binder was evaluated, as it shows to be heat and fire resistant [30]. These materials were used for the production of thermal-insulation boards with economic profit while ensuring environmental safety of the climate and human beings.

2. Materials and testing methods

2.1. Materials

2.1.1. Fibers

Rye straw, barley straw, wheat straw, oats straw, rice straw, flax boon and rice husk were used in the experimental program.

The chopping of straw was carried out on a drum-type straw chopper. Straws were chopped and used with a tube length of 20–40 mm, except for rye straw where a tube length of not more than 80 mm was used.

Flax boon is the main waste of primary processing of flax in the production of flax fiber and is 60%–70% of its weight. When the fiber is separated during the process of mint and flutter, the flax stems are destroyed, and the falling, lumpy parts form a boon. The particle size of the boon used was no more than 15 mm in length and from 0.3 to 1.5 mm in thickness.

Rice husk is obtained as a result of peeling rice grains. The husk is an elongated hemisphere with a length of 5–10 mm and a width of 1.5–2 mm.

The above mentioned fiber sizes were used to measure physical and mechanical characteristics presented below in Section 3.1, whereas for measuring the moisture absorption, the effect of humidity on the thermal conductivity and for full-scale testing (as shown in the Sections 3.3, 3.4 and 4), rye straw with a tube length of 20–40 mm and flax boon after sifting through a vibrating screen with a mesh size of 5 mm were used.

2.1.2. Binders

Three types of binders were used: liquid glass, emulsion of PVA (polyvinyl acetate) and latex. The sodium liquid glass corresponds to standard GOST 13078-81 [31], having the following technical characteristics: silicate module 2.9; pH 11–12; viscosity 0,0194 (N·s)/m^2; density of 1.45–1.47 g/cm^3; thermal conductivity of 0.23 W/(m·K). Emulsion PVA brand D51V produced by the company Poliplast (Belarus) is a homopolymer coarse dispersed polyvinyl acetate, not plasticized and stabilized with polyvinyl alcohol, having thermal conductivity of 0.19 W/(m·K). Polyvinyl acetate emulsion meets the requirements of GOST 18992-80 [32]. Latex is an aqueous dispersion of polymers. In the experimental program, styrene butadiene styrene latex grade CKS-65GP was used, which meets the requirements of GOST 10564-75 [33], with thermal conductivity of 0.22 W/(m·K).

2.1.3. Preparation of specimens

Initially, all components of the experimental compositions were weighed according to the specimen size and composition. The binder was added to the fiber and mixed. The prepared mixture was evenly placed in the mold and covered with a lid. The mold was then placed on a press and the mixture was consolidated at a molding pressure of 0.2–0.4 MPa. After the end of molding, the lid was fixed and the material was kept in the mold for at least

6 hours. The specimens were then removed from the mold and placed in a drying chamber at a temperature of 50 °C. The dimensions and shapes of the specimens (cubes or plates) were determined by the type of test being carried out.

To evaluate the influence of the fiber and binder type on the physical and mechanical properties, 13 different compositions were used in the experimental program.

Each one of the compositions 1–7 were prepared using one the following fiber types: Rye straw, barley straw, wheat straw, oats straw, rice straw, flax boon and rice husk, and using liquid glass as a binder.

Compositions 8–13 were done using two types of fibers. Rye straw and flax boon were used in compositions 8–10, whereas rice straw and husk were used in compositions 11–13. In compositions 8–13, rye and rice straw were added as a large filler, and flax boon and rice husks as a small one. The mass fraction of straw in the total filler consumption was 0.7. To evaluate the influence of the binder in these compositions of two fiber types, three binders were used (sodium liquid glass, latex and PVA emulsion) in an amount of 1.4 of mass fraction of dry matter.

2.2. Testing methods

Density, humidity, compression strength at 10% of linear strain and bending strength were determined in accordance with the state standard GOST 17177-94 [34], which state similar procedures to standards EN 826 [35] for the compression test and EN 12089 [36] for the bending test.

2.2.1. Determination of compression strength

The tests were carried out on specimens in the form of cubes with an edge size of 100 mm. Before the test, the specimens were held for at least 6 hours at a temperature of 23 ± 5 °C and relative humidity of 50 ± 5%. Strength determination was carried out on five specimens for each composition. The test specimens were placed centrally between two parallel plates of a compression testing machine. The test specimens were compressed at a constant rate of 0.1 × d per minute, where d is the thickness of the test sample. The tests were done until a compression deformation of 10% was reached. The compression strength at 10% deformation was calculated from the equation:

$$\sigma_{10} = \frac{F_{10}}{A_0} \tag{1}$$

where:

F_{10} - load at 10% compression deformation, N;A_0 - cross-sectional area of the test sample, mm^2.

2.2.2. Determination of bending strength

The tests were carried out on specimens in the form of beams 80 mm thick, 150 mm wide and 450 mm long. Before the test, specimens were held for at least 6 hours at a temperature of 23 ± 5 °C and a relative humidity of 50 ± 5%. Determination of strength was carried out on five specimens. The test was carried out on a three point bending test, placing the specimen on two cylindrical supports with 80 mm in diameter each. The distance between the axis of the supports was 390 mm. From the end surface of the sample to the axis of support, the distance was 30 mm. The load on the sample was applied through a cylinder of 80 mm in diameter, over the entire width of the sample at an equal distance from the supports and moving at a speed of 10 mm/min. The bending strength was calculated from the equation:

$$\sigma_b = \frac{3 \times F_m \times L}{2 \times b \times d^2} \tag{2}$$

where:

F_m - maximum load, N;L - distance between supports, mm;b - width of the test specimen, mm;d - thickness of the test specimen, mm.

2.2.3. Determination of density

The density of the material was determined on cube specimens with an edge size of 100 mm. First specimens were dried to constant weight in a drying chamber at a temperature of 50 °C. After drying, the specimens were weighed. The length, width and thickness of the specimens were then measured and its volume was calculated. The measurements were carried out on five specimens. The density was calculated by the equation:

$$\rho = \frac{m_1}{V} \tag{3}$$

where:

m_1 is the mass of the dried sample, kg;V is the volume, m^3.

2.2.4. Determination of thermal conductivity

The thermal conductivity of the investigated materials was measured according to the heat flow meter method, following the procedure of the Belarussian standard STB 1618 [37] which is in accordance with the standard EN 12667 [38]. The thermal conductivity was determined on specimens in the form of slabs measuring 250 × 250 × 30 mm. First, the specimens were dried to constant weight in a drying chamber at a temperature of 50 °C. After drying, the specimens were placed in the chamber of the equipment ITP-MG4 «250» to determine the thermal conductivity (λ_{25}). The surface temperature of the heater plate was 40 °C, and the surface temperature of the refrigerator plate was 10 °C. Tests were conducted on five specimens for each composition.

2.2.5. Determination of humidity

Before the test, the sample was weighed. The specimens were then dried to constant weight in an oven at 50 °C. The specimen was considered dried to a constant mass if the weight loss after repeated drying within 0.5 hours does not exceed 0.1%. After drying and before weighing, the sample was cooled in a desiccator over calcium chloride. Humidity was calculated by the equation:

$$W = \frac{m_1 - m_2}{m_2} \times 100 \tag{4}$$

where:

m_1 - mass of the specimen before drying, g;m_2 - specimen weight after drying, g.

2.2.6. Electronic microscopy analysis

To understand the factors that determine the physical and mechanical characteristics of the thermal insulating flax boon plates, the microstructure of rye and flax was examined using an electronic microscope of JSM-5610 LV type. During the examination, images of cross and longitudinal sections of dried stems of rye and flax straw were obtained.

2.2.7. Determination of water absorption

The water absorption was determined according to Belarussian standard STB EN 12088 [39] and in accordance with the procedure indicated by Franchuk et al. [40]. In this test, a desiccator method for determining absorption humidity was used. Specimens weighing 5 g were taken. First, specimens were dried to constant weight in an oven at 50 °C, and then placed inside the desiccator. Solution of sulfuric acid was used to maintain the specified relative humidity in the desiccator. Specimens were periodically weighed, 2–3 times a month, until they reached a constant mass. Tests were carried out on three specimens for each composition. At the end of the absorption process, the moisture content is calculated at different values of the air relative humidity according to the equation:

$$W_m = \frac{m_1 - m}{m_2} \times 100 \quad (5)$$

where:

m_1 - maximum mass of a moistened sample of material at the end of the experiment, g;m - mass of the dry sample before the test, g.

2.2.8. Effect of humidity on the thermal conductivity

Determination of the dependence of the thermal conductivity of specimens from humidity was carried out according to the method proposed by Rubashkina [41]. Thermal insulating specimens based on rye straw and on a mixture of rye straw and flax boon, in a dry state, were used to this test, having density of 230 kg/m^3, and thermal conductivity (λ_{25}) equal to 0.056 and 0.047 W/(m•K), respectively. The specimens in the form of plates with a size of 250 × 250 × 30 mm were kept in the chamber above water for 2, 3, 5, 10 and 25 days at a relative humidity of 97%–98%. To get the effect of humidity on the thermal conductivity, the specimens were removed from the chamber and the density and thermal conductivity in the humid state (λ_W) were determined after 2, 3, 5, 10 and 25 days of conditioning inside the chamber.

2.2.9. Full-scale tests

The effectiveness of straw-boon plates was evaluated by full-scale tests of insulation in a building construction, monitoring the main thermophysical characteristics and with control of the general state of the structures.

Full-scale tests were conducted on an individual residential one-story house with a wall height of 3 m, located in Polotsk (Belarus). Brick walls with a thickness of 250 mm were built from ceramic full-bodied bricks, measuring 250 × 120 × 65 mm on a cement-lime masonry mortar. Insulating plates with 100 mm of thickness were fixed to the walls using dowels with a galvanized metal core. A ventilated facade system was applied on the brick walls. Finishing of ventilated facades of the house was done with steel panels with a polymer coating. Thermocouples and sensors were installed at an height of 1.2–1.9 m from the floor level. A fragment of the section of the outer wall of the residential house with the installed thermocouples and heat flow sensors from the inside is shown in Fig. 1.

Two external walls with a ventilated thermal insulation system were used in the tests, one of them with thermal insulation made from rye straw (wall 1) and another with straw-boon plates (wall 2). In the wall structure, thermocouples and heat flow sensors were installed for each heat insulating plate under study (Fig. 2).

The readings of temperature and density of heat flows were recorded by the device RTP-1-16T, assembled at the production company "Promtis" (Minsk, Belarus), and consisting of a microprocessor multichannel, digital voltmeter of constant voltage, primary heat flow converters and primary temperature converters connected to functional groups. Sensor readings from temperature and heat flux data were taken every five minutes, during the autumn-winter-spring period. As an example, the time period from 10 to 29 of January 2016 was considered (as the coldest period in winter).

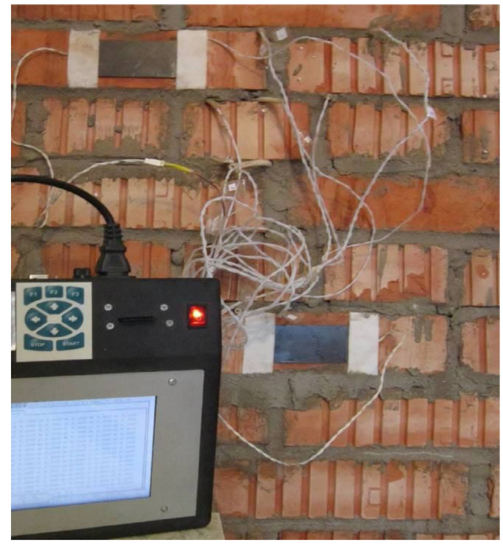

Fig. 1. Location of heat flow sensors and thermocouples on the wall (view from the inside).

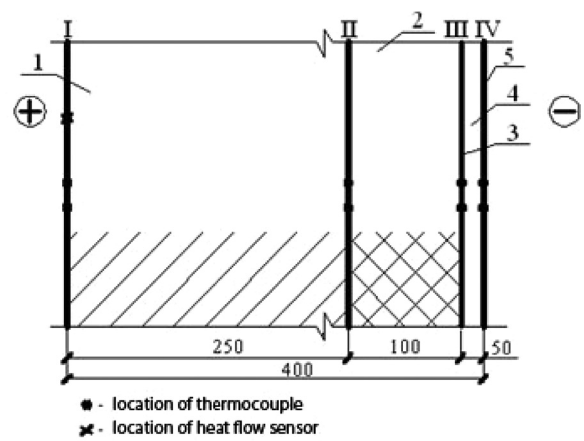

Fig. 2. The layout of thermocouples and heat flow sensors along the external wall section with a ventilated thermal insulation system: 1 – full-size ceramic bricks; 2 – thermal insulating plate; 3 – wind protection; 4 – air space; 5 – steel metal sheet; I, II, III, IV – lines of wall layers.

3. Laboratorial test results

3.1. Physical and mechanical characteristics of thermal insulating materials

The main physical and mechanical characteristics of thermal insulating materials based on vegetable raw materials (including straw of cereals, flax and rice husks), prepared in the laboratory of the Department of Construction Industry of Polotsk State University, are given in the Table 1.

The physical and mechanical characteristics obtained for the compositions 3 and 6 (based on wheat straw and flax boon) are confirmed by the data given by other authors [42,43].

Among the studied materials from straw cereals (compositions 1–5), samples based on crushed rye straw (composition 1) have one of the best physical and mechanical characteristics. At practically equal values of density and thermal conductivity, the compression strength in composition 1 exceeds the values of compositions 2–5 by 21%–52%, and bending strength by 26%–64%, which is probably due to the greater "stiffness" given by the stems of rye straw.

Among samples based on other waste of plant growing (compositions 6 and 7), composition 6 has the best physical and mechanical characteristics. The compression strength in a thermal insulating material based on flax boon is comparable to that of composition 7, and its bending strength is practically twice as much. The thermal conductivity of composition 6 is similar to the materials based on cereals straw (compositions 1, 3 and 4) and 23% lower than in composition 7.

Table 1
Physical and mechanical characteristics of thermal insulating materials.

Composition			Average physical and mechanical characteristics*			
Number	Fiber	Binder	Density (kg/m^3)	Compression strength (MPa)	Bending strength (MPa)	Thermal conductivity (λ_{25}) W/(m·K)
1	Rye straw	Liquid Glass	215 (5.7)	0.35 (0.023)	0.82 (0.051)	0.059 (0.003)
2	Barley straw	Liquid Glass	205 (6.24)	0.27 (0.021)	0.58 (0.042)	0.063 (0.004)
3	Wheat straw	Liquid Glass	220 (5.91)	0.30 (0.026)	0.65 (0.038)	0.056 (0.004)
4	Oats straw	Liquid Glass	200 (4.74)	0.27 (0.025)	0.60 (0.041)	0.058 (0.004)
5	Rice straw	Liquid Glass	210 (5.7)	0.23 (0.021)	0.50 (0.038)	0.062 (0.005)
6	Flax boon	Liquid Glass	230 (5.05)	0.48 (0.031)	0.62 (0.047)	0.054 (0.004)
7	Rice husk	Liquid Glass	230 (5.43)	0.50 (0.032)	0.34 (0.026)	0.068 (0.004)
8	Rye straw and flax boon	Liquid Glass	225 (4.74)	0.60 (0.03)	0.95 (0.06)	0.049 (0.003)
9	Rye straw and flax boon	Latex	230 (6.12)	0.64 (0.036)	1.03 (0.066)	0.057 (0.005)
10	Rye straw and flax boon	Emulsion PVA	225 (5.7)	0.65 (0.029)	1.00 (0.065)	0.058 (0.004)
11	Rice straw and husk	Liquid Glass	230 (6.56)	0.43 (0.026)	0.68 (0.056)	0.058 (0.003)
12	Rice straw and husk	Latex	225 (6.67)	0.47 (0.03)	0.72 (0.053)	0.067 (0.005)
13	Rice straw and husk	Emulsion PVA	235 (7.14)	0,44 (0.036)	0.70 (0.058)	0.069 (0.004)

* - Numbers between brackets correspond to the standard deviation.

The use of composite material made from two fiber component made it possible to improve the physical and mechanical characteristics of compositions 8–13 in relation to compositions 1–7 with one-component fibers. The table shows that the results of compositions 8–10 exceed those of compositions 11–13 for compression strength by 36%–48%, bending strength by 40%–43% and thermal conductivity of compositions 8–10 is lower by 15 –16%. Thus, specimens based on a mixture of rye straw and flax boon (compositions 8–10) should be considered more effective than thermal insulation materials based on rice straw and husks (compositions 11–13).

Using a mixture of chopped straw and flax boon makes it possible to create an interpenetrating structural system «frame in the frame» of the thermal insulation mass. The first frame is formed by the large fibers (chopped straw) and the second frame is formed by the small fibers (flax boon). The frame of a small filler occupies the space of the existing contiguous voids in the frame of a large filler. Thus, a rigid structure with higher strength characteristics is formed.

Mechanical properties of a structural system «frame in the frame» are probably provided by strength and stiffness of the fibers, by the strength and stiffness of the formed contacts between the large fibers, by the binder and small fibers, by the adhesion of solidified binder to the surface of straw and flax boon as well as by the density of the fiber mixture [44].

As a binder, the most interesting is liquid glass. Unlike latex and PVA dispersion, liquid glass significantly increases the fire resistance of materials [45], including combustible plant fillers.

To reduce solubility, it is offered to add sodium hexafluorosilicate, gypsum, two-component additives of lime and gypsum, as well as chalk and gypsum. The optimal amount of additives is 8%–10%. With such an addition, the solubility of liquid glass with Na_2SiF_6 is no more than 14%, with the formation of an insoluble residue in an amount of 86%–89%. The addition of gypsum makes it possible to obtain an insoluble residue equal to 86%–90% by weight. The two-component additive of gypsum and chalk increases water resistance of liquid glass to 88%–90%, and the addition of lime and gypsum up to 92%–95%. However, when choosing an additive, it should be taken into account that, based on hygienic requirements, the amount of added sodium hexafluorosilicate should not exceed more than 10% of the weight of the liquid glass on dry matter. The use of gypsum, taking into account its rapid entry into the chemical reaction, makes the equal distribution of the binder throughout the whole mass of flax boon mixture at the mixing stage technologically unachievable. Thus, based on water resistance index for liquid glass with module 2.9, the most appropriate is the use of two-component additives $CaCO_3 + CaSO_4$ and $Ca(OH)_2 + CaSO_4$.

Fig. 3. Cross section of the rye stem (fragment, 200x magnification).

3.2. Electronic microscopy

3.2.1. Rye straw specimen

The study of the rye straw cross section specimen (Fig. 3) made it possible to see two distinct structural parts of the stem structure. The inner part with capillaries with cross section of 40–90 µm, is divided by thin transparent partitions with a thickness of less than 0.5 µm, being 50%–60% of the total volume of the stem wall structure and resembles the structure of honeycombs. The outer part is represented by 5–40 µm capillaries with partitions of 1–3 µm in thickness and occupies a volume of 40%–50%. The stem of the straw has shells from the outer and inner sides that would be able to protect from damage and destruction. In the longitudinal section of rye straw specimen (Fig. 4) it was noted that capillaries in the inner part of the stem have cross partitions spaced from 50 to 100 µm, and form cells that are close to cylindrical shape. The outer part consists of longitudinal capillaries separated by partitions spaced from 150 to 500 µm. The diameter of the capillaries gradually decreases from the base to the top of the stem. Based on these comparisons of the geometrical parameters of the cellular structures, it can be concluded that the inner part of the stem has different insulating properties in comparison with the outer part.

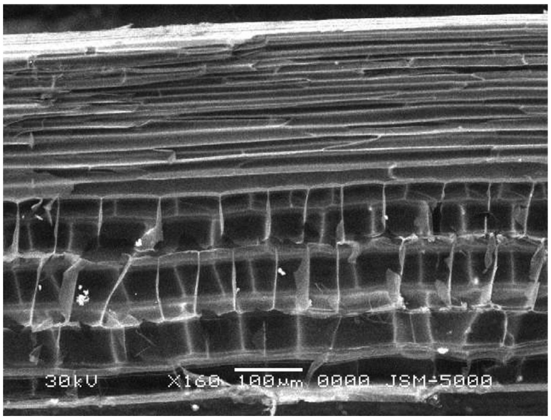

Fig. 4. Longitudinal section of the rye stem (160x magnification).

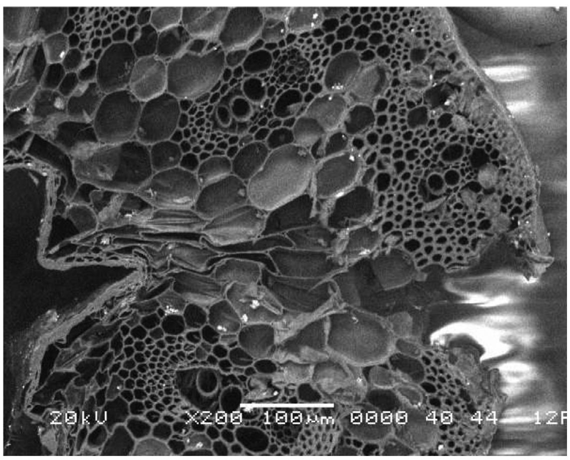

Fig. 5. Cross section of deformed rye (fragment, 200x magnification).

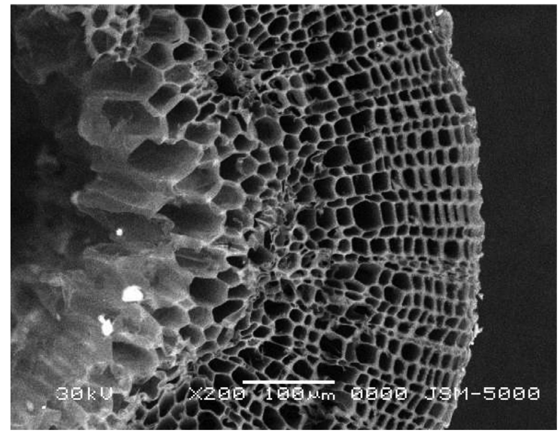

Fig. 6. Cross section of the flax stem (fragment, 200x magnification).

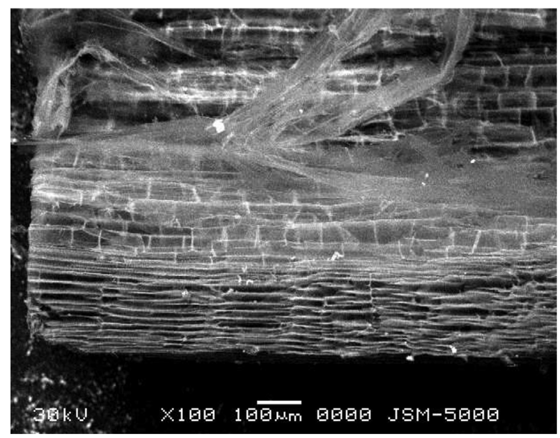

Fig. 7. Longitudinal section of the flax stem (100x magnification).

When molding plates the walls of rye stalks undergo significant deformations, leading to the destruction of the capillary structure of the rye straw cylinder. In the result of stem deformation, structural breaks in the outer part and capillaries crumpling in the inner part are formed (Fig. 5). Damage to the straw stems, obtained during the formation of straw plates with increasing molding pressure, can probably have a significant effect on the decrease in the physical and mechanical characteristics of the insulation.

The inner part of the straw stalk has a smaller cellular structure, compared to the structure of expanded polystyrene. The size of the cells of expanded polystyrene is 80–150 µm [46], which is 1.5–2 times the size of the cells of the structure of the inner region of the stem of the straw. In this case, the thickness of the partitions in the inner region of the straw is 0.5 µm, which is 2–4 times thinner than the width of the expanded polystyrene partitions equal to 1–2 µm.

3.2.2. Flax specimen

Microscopic figures of cross and longitudinal sections of flax stem (Figs. 6 and 7) allowed to see the presence of capillary structure which is similar as for rye stem, however having some peculiarities. Inner capillary part comprises about 15%–20% of the whole structure of the flax stem. Inner protective shell is absent. In the cross section, capillaries of 30–70 µm size are of the same form as of rye straw. The capillaries are separated each 50– 120 µm in the longitudinal direction by a thin transparent partition with a thickness of less than 0.5 µm.

It should be noted that in the process of the technological separation of fiber, the flax stem wall is destroyed into separate fragments, resulting in a flax boon. At this stage of production, the inner part of the stem wall is almost completely destroyed, and the partitions of the remaining part of the capillaries are significantly damaged by deformations. As a result, the structure of the flax boon consists mainly of the outer part of the flax stem wall, which is a parallel capillary with a size of 5–30 µm with transverse walls of 1–2 µm thick through 100–300 µm. In the outer part of the stem, the capillaries have a cross-sectional shape that is close to square or rectangular; a sufficiently clearly oriented structural framework of longitudinal partitions is formed, which is caused by the successive arrangement of the capillaries from the inner part to the outer shell.

In the images of sections, it was noted that the partitions of the capillaries of the outer part of the rye and flax stems are 4 to 6 times thicker than the capillaries of the inner part. This indicate that the strength characteristics of rye straw and flax boon are achieved probably mostly due to the outer parts of stems formed during growth of the capillary structure.

The use of large fibers, obtained by cutting stems of straw with a length of 20–40 mm, a properly selected ratio of straw and flax boon, as well as a molding pressure of 0.02–0.03 MPa are important parameters that influence the preservation of the capillary structure of straw (especially thin-walled cells of capillaries of the inner part of the stem) during the molding, in order to produce rye straw and flax boon plates with high thermal engineering characteristics.

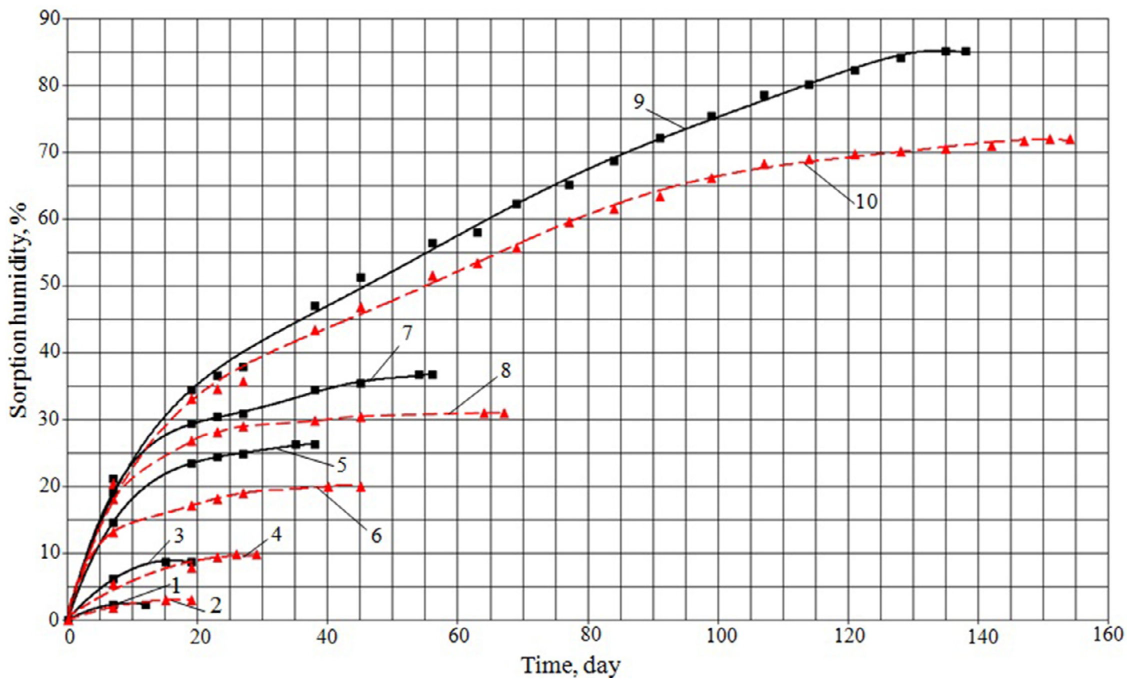

Fig. 8. Kinetics of water vapour absorption by: rye straw material at the relative air humidity: 1 – 40%; 3 – 60%; 5 – 80%; 7 – 90%; 9 – 97%; mixture of rye straw and flax boon at the relative air humidity: 2 – 40%; 4 – 60%; 6 – 80%; 8 – 90%; 10 – 97%.

3.3. Water absorption

Investigation of the water absorption on two fiber type plates made of rye straw and flax boon (called straw-boon plates) was carried out in order to determine the necessary indicators for the calculation of the moisture regime of the enclosing structures. From the analysis of the obtained data (Fig. 8) it is observed that the water absorption of the material based on chopped rye straw at relative humidity of air up to 60% is lower than the water absorption of the material based on a mixture of chopped rye straw and flax boon by 11.2%. However, at an air humidity of 80%, the water absorption of the rye straw material is 26.3%, which exceeds by 32% the moisture of the material based on a mixture of rye straw and flax boon, equal to 20%. At a relative humidity of 97%, the water absorption of the rye straw material reaches 85.2%, which is 18% higher than the material based on a mixture of rye straw and flax boon, equal to 72%.

Also, an important characteristic for thermal insulating materials is the kinetics of water vapor absorption at a certain value of the relative air humidity. At the relative air humidity 40%, the humidity absorption of the rye straw material increases during 7 days up to 2,3% (specimen 1), when for the material based on the mixture of rye straw and flax boon reaches up to 3% during 15 days (specimen 2). When comparing specimens 5 and 6 at the relative air humidity 80% it is evident that for the period of 35 days the humidity of the rye straw material is 32% more than of the material based on rye straw and flax boon during the same period of time. Specimens 9 and 10 reflect the consumption of water vapour by the materials at relative air humidity 97%. At the same time the water absorption of the rye straw material is 21% more than that of the material based on the mixture of rye straw and flax boon for the period of 135 days. It should be noted that the process of absorption of the straw-boon material ends in 151 days, which is 16 days longer than for the rye straw material, and at the end of the water vapor absorption process, the absorption humidity of the material based on a mixture of rye straw and flax boon is 15% less, than that of the rye straw material. After the end of the absorption process, stabilization of water vapor absorption by the material is observed in all cases.

The process of absorption of water vapor by the rye straw material proceeds more intensively than by the straw-boon material, which is confirmed by the large values of absorption humidity. Consequently, it can be assumed that in the course of operation, the thermal conductivity of the material on the basis of a mixture of rye straw and flax boon will be lower than that of the rye straw material, and regarding thermal behaviour, straw-boon plates must be better than those made of straw.

3.4. Effect of humidity on the thermal conductivity

Figs. 9 and 10 show the thermal conductivity ratio (λ_W/λ_{25}) between the humid and dry plates after being kept in the chamber for 2, 3, 5, 10 and 25 days.

When the specimens were held in sealed chambers after 25 days, the value of the thermal conductivity of plates based on rye straw and on a mixture of rye straw and flax boon increased by 2.1 times and 1.8 times, having thermal conductivity equal to 0.119 and 0.084 W/(m·K), humidity of 54% and 39% and a density of 352 and 317 kg/m^3, respectively. Structural system «frame in the frame» of the straw-boon plates, which provides a significant reduction in voids, as well as a lesser absorption capacity of flax boon, significantly reduces the absorption from the air, in comparison with that of the rye straw plates.

An approximating curve was adjusted to the experimental data on the dependence of the thermal conductivity on humidity, using a regression analysis as also done in previous studies [47]. The results are shown in the Figs. 9 and 10. The data is satisfactorily approximated by the exponential function of the type:

$$\lambda_W = \lambda_{25}.e^{k.W} \tag{6}$$

where:

λ_{25} - is the thermal conductivity of dry matter, W/(m·K);W - humidity of the material, %;k - coefficient.

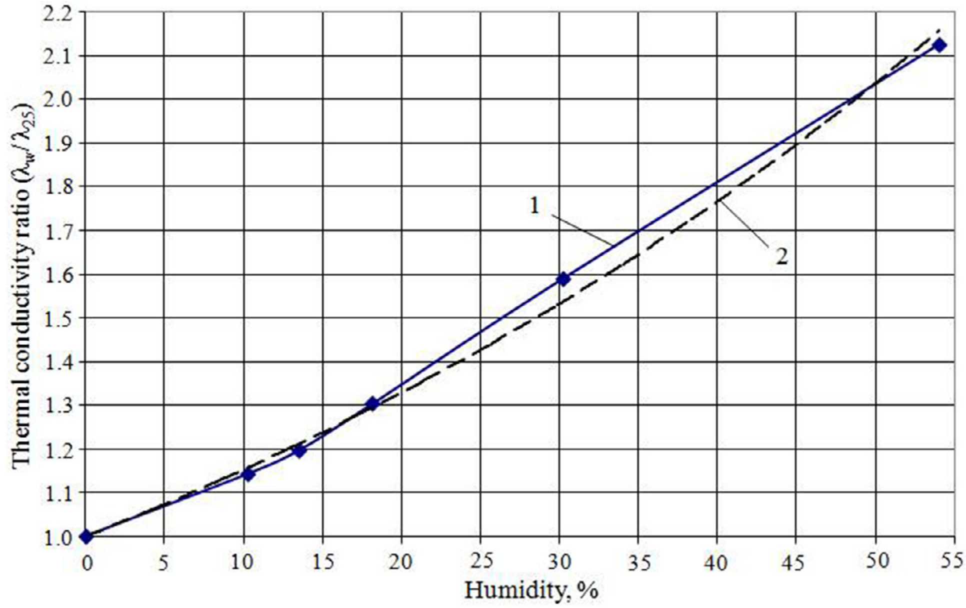

Fig. 9. Dependence of the thermal conductivity ratio on the humidity of rye straw plate: 1 – experimental data; 2 – approximating curve.

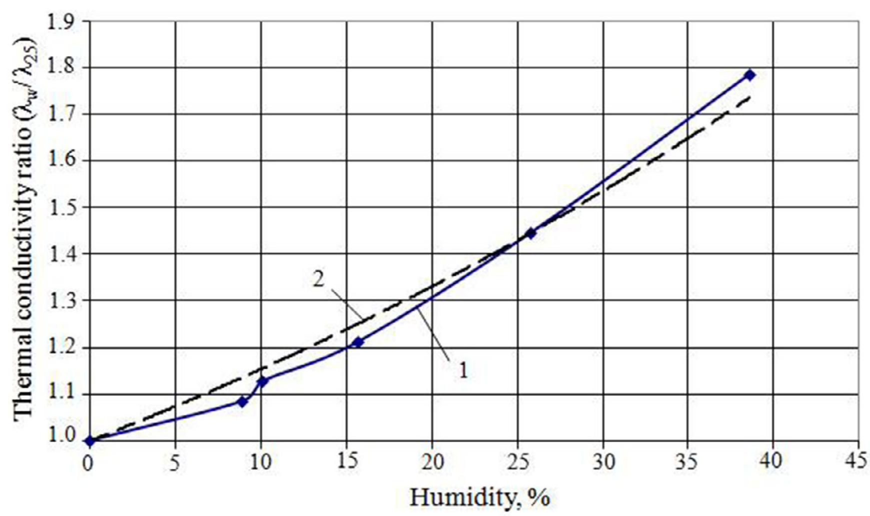

Fig. 10. Dependence of the thermal conductivity ratio on the humidity of straw-boon plate: 1 – experimental data; 2 – approximating curve.

Relevant correlation coefficients (R) were obtained using coefficient k equal to 0.014, being equal to 0.9953 for rye straw plates and 0.9806 for straw-boon plates.

From the results of the experimental data analysis, it can be said that the change of humidity considerably influences on basic physical characteristics of thermal insulating rye straw and straw-boon plates. An increase in the humidity index of thermal insulating plates leads to an increase in the density of the specimens by 38%–53% and in the thermal conductivity in 1.8–2.1 times.

4. Full-scale test results

Fig. 11 shows the temperature distribution along the thickness of the enclosing structure of wall 1 (with rye straw plates) and wall 2 (with rye straw and flax boon plates), over the period of 20 days. The temperature values were taken as average values of the readings from 22 hours to 6 hours.

The layout of the temperature distribution shows that for the external wall 1 the average temperature of inner surface on the line I is 1.6 °C less than for the wall 2. For the minimum outside temperature of −22.6 °C the temperatures of inside wall surface on the line I differ by 2 °C. The average value of the temperature of thermal insulating plate on the line II of the wall 1 is 2.4 °C less than of the wall 2. On the line III the average value of the temperature of the rye straw insulation is decreasing by 1.9 °C in comparison with that of the insulation based on the mixture of rye straw and flax boon. The amplitude of average temperature for the wall 1, with rye straw plates, is 26 °C, and for the wall 2 it is 30 °C. For the minimum value of the outside temperature the temperature amplitudes are increasing up to 29 and 34 °C, respectively. Using the experimental data, the thermal resistance of the walls was determined by the ratio of the temperature difference between the inside and outside surfaces to the heat flow density passing through the wall structure. The thermal resistance of the wall with straw-boon plates is 1.90 (m^2·K)/W which is 30% more than the thermal resistance of the wall with rye straw plates, equal to 1.46 (m^2·K)/W.

Humidity in the insulating plates was measured, after the end of full-scale tests in April 2016, when positive temperatures were established on the outside, which make it possible to dismantle the

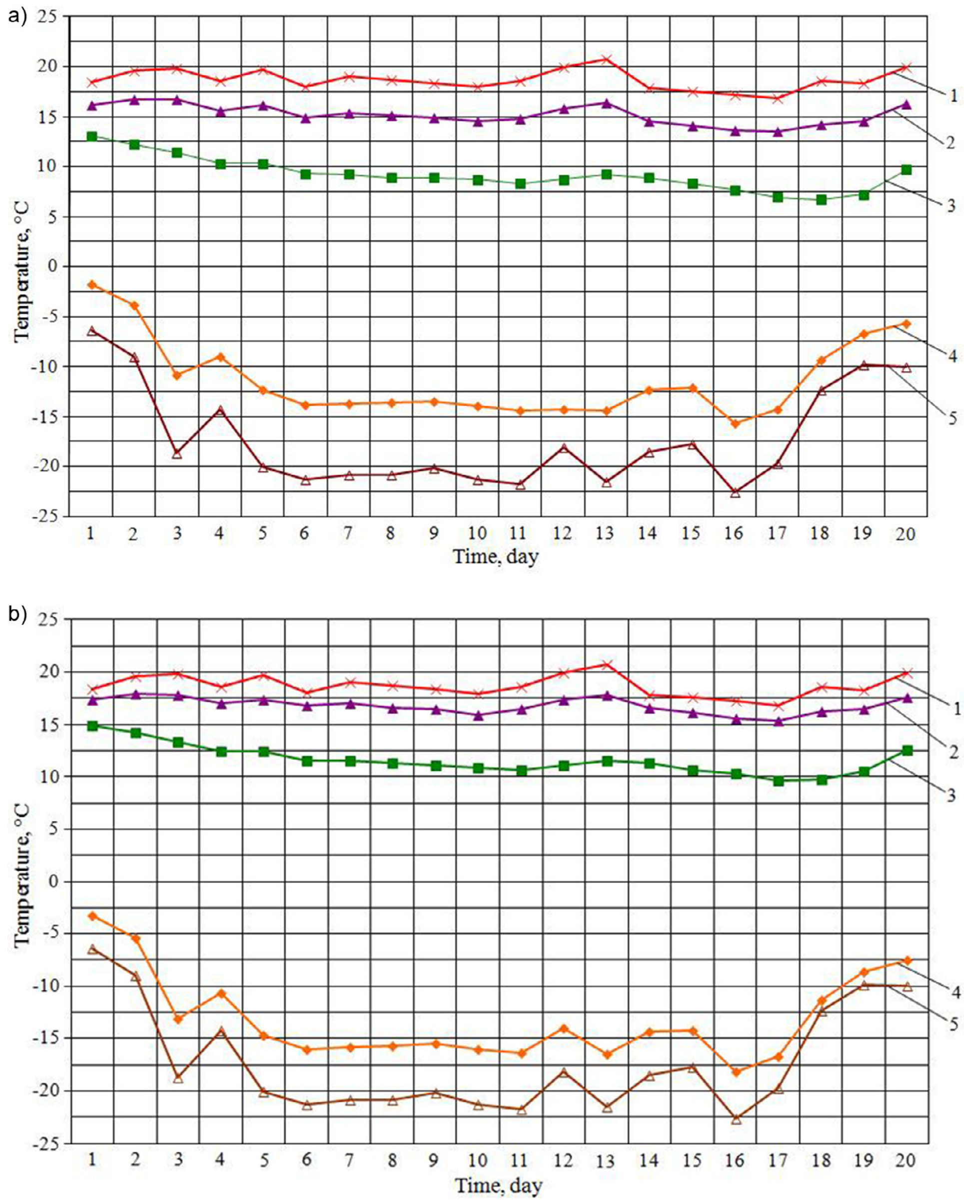

Fig. 11. Temperatures of walls with a ventilated thermal insulation. system: a – with rye straw plate; b – with rye straw and flax boon plate; 1 – inside temperature, °C; 2 – temperature of the 1st layer material on the line I°C; 3 – temperature of thermal insulating material of the 2nd layer on the line II°C; 4 – temperature of thermal insulating material of the 2nd layer on the line III, °C; 5 – outside temperature, °C.

plates for preparation of the samples, when moisture in the material was still high. The humidity in the insulation plates was determined on samples measuring 100 × 100 × 100 mm, which were cut from thermal insulating slabs. The obtained samples across the thickness of the test plates were sawed into five equal specimens, each one with 20 mm in thickness. Each specimen was weighed and dried to constant weight in an oven at 50 °C. The specimens were considered dried to constant weight if the weight loss after repeated drying for 0.5 hours did not exceed 0.1%.

After drying, the specimens were cooled in a desiccator over calcium chloride, before weighing. Humidity was then calculated. According to the obtained data, the moisture distribution curve was plotted along the thickness of the insulation.

The changes in humidity along the thickness of the material are shown on Fig. 12. Humidity at a thickness of 100 mm correspond to those of the line wall layers II. The average humidity value of the rye straw material is 19%, which is 38% more than the humidity of the material based on the mixture of rye straw and flax boon (12%). On the outside line III the humidity slightly differ, being 19.1% for rye straw plates and 11.8% for rye straw and flax boon plates.

At the joints of the insulation and for the wall 1 on the line II the humidity is decreasing to 16,2%, which is 53% more than for the wall 2 (10,6%). At a distance of 35–45 mm from the line III a maximum increase in the humidity is observed in rye straw plates as well as in rye straw and flax-boon plates, up to 22.2 and 14%, respectively. It is necessary to note that the part of the greatest humidification of thermal insulating plates (0–45 mm tickness) is connected with the vertical air circulation along the outer surface of plates, facilitating the evaporation of moisture from the surface layers of the insulation.

During summer period, the humidity of straw and straw-boon plates decreases to 8 and 5% respectively, providing effective operation of the insulations in winter. The ventilated system has already been functioning for 3 years. Damages and shifts of thermal insulating plates are not observed. Thus, verification in situ

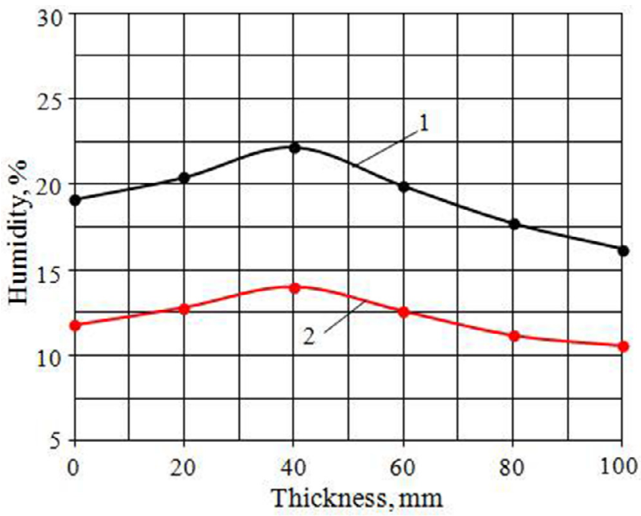

Fig. 12. Humidity distribution along the thickness of thermal insulating plate: 1 – rye straw insulation (wall 1); 2 – insulation based on rye straw and flax-boon (wall 2).

tests of thermal insulating material confirm the possibility of using straw-boon plates as an effective wall insulation when applying a ventilated thermal insulation system. Following the results of the research, technical requirements for straw-boon plates TS BY 300220696.060-2011 «Straw-boon construction thermal insulating plates» has been developed and registered.

5. Conclusions

The best thermophysical and mechanical performance of effective insulations based on vegetable raw materials was achieved by forming a composite structure of a material of two fibers of different size and shape, which allows to ensure the optimal structure of thermal insulating materials.

Electronic microscopy of longitudinal and cross sections of rye straw and flax boon made it possible to establish the presence of inner and outer parts in their structure, which differ significantly in structure. The inner part of the straw of rye and flax is similar in structure to that of expanded polystyrene (but less than 1.5–2 times), which explains the high thermal insulation properties of the resulting composite. In the outer part of the stems, the size of the capillaries are 2–8 times smaller in cross sections than the size of the inner part capillaries, and the thickness of the partitions is 2– 6 times larger than the size the inner part partitions. Such a structure of the outer part, in comparison with the inner one, ensures the stiffness and strength of the stems of rye straw and flax boon and essentially determines the strength characteristics of the resulting thermal insulating material.

The moisture absorption of the material from a mixture of rye straw with flax boon at the relative air humidity of 80%–97% is 15–24% less than that of rye straw material, and the absorption process lasts 5–6 days longer. The thicker structure of rye straw and flax boon plates which provides a significant reduction in voids, as well as less absorption capacity of flax boon significantly reduce the absorption of moisture from the air by the insulation compared to that of the rye straw plates. For these reasons, regarding the absorption of moisture, rye straw and flax boon plates have higher physical characteristics than rye straw ones.

Based on the experimental results, a relation was obtained that allows to predict the values of the thermal conductivity as a function of the moisture content of the material for rye straw and rye straw and flax boon plates. Practical application of the equation is possible in theoretical calculations of the thermo physical parameters of the designed walls, as well as in predicting the thermo physical characteristics of the enclosing structures with the use of thermal insulating plates based on rye straw and a mixture of rye straw and flax boon under operational conditions.

Increase in the amplitude of temperatures by 4–5 °C was obtained with the use of rye straw and flax boon plates in comparison with that of rye straw due to: the microstructure of the components of the fibers; correctly selected ratio of components, minimizing the voids in the plates; lower operating humidity of the composition. The increase in the amplitude of temperatures achieved during the winter period makes it possible to reduce the consumption of energy and reduce the costs of heating in the buildings.

Taking into account the current situation on the market for thermal insulating materials, the development of an ecologically safe insulation with high thermal engineering characteristics based on rye straw and flax boon with the use of liquid glass as a binder is a promising direction for the successful processing of agricultural plant waste.

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