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Research of Physical Properties of Straw for Building Panels

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Abstract: *The development of new thermal insulation materials needs to evaluate properties and structure of raw materials, technological factors that make influence on the thermal conductivity of material. One of the most promising raw materials for production of insulation material is straw. The use of natural fibres as insulation is closely linked to the ecological building sector, where selection of materials is based on factors including recyclable, renewable raw materials and low resource production techniques.*
In current work results of research on structure, thermal conductivity, water vapour permeability and short term water immersion of triticale straw for production of thermal insulating straw panels are presented. Straw panels withdifferent densitywere prepared for thermal conductivity measurement. It was determined that lowest thermal conductivity of straw is reached when straw density ranges from 80kg/m^3 to 120 kg/m^3. It was found that the macrostructure that changes with density increase has the great effect on thermal conductivity of materials. At the density range of 120-190 kg/m^3 increase of thermal conductivity values are observed. Water vapour permeabilitywas analysed at the density ranges from 80 kg/m^3 to 156 kg/m^3. Vapour permeability values grew with density increase from 2 to 2.5. Short term water absorption was evaluated by two parameters - as water absorption coefficient due to capillary action and short term water absorption by partial immersion. Water absorption coefficient shows sudden mass increase within the first 10 minutes and subsequent slow mass increase. Short term water absorption values show significant weight increase during 48 hours, which reaches 100 percent by mass.

Keywords:*triticale straw, thermal conductivity, water vapourpermeability, short term water absorption water absorption coefficient, macrostructure.*

I. INTRODUCTION

In current time in global market wide choose of thermal insulation materials are supplied. Newest thermal insulation such as vacuum insulation panels, gas-filled panels, aerogels, and phase change materials [1] or ecological thermal insulation such as fiberboards, loose fill insulation or panels from different plants or their tails [2-4] takes a part of this market.

In the last 20 years cellulose based plant fibers have gained importance as raw material for thermal insulations. The use of natural fibers in insulation is closely linked to the ecological building sector, where selection of materials is based on factors including recyclable, renewable raw materials and low resource production techniques [5, 6]. Moreover, thermal insulation from cellulose based plant fibers are used for sound absorption purpose [7-10]. One of main requirements for building envelopes is to ensure acoustic comfort, especially in multi-dwelling buildings [11, 12]. Plant fibers for sound absorption are used inside buildings for floors, enclosures, partitions and ceiling insulation. Outdoor following products are used as sound-absorbing walls (fences) to protect against of car noise [13].

Straw is an agricultural by-product, the dry stalks of cereal plants, after the grain and chaff have been removed. Straw makes up about half of the yield of cereal crops such as barley, oats, rice, rye, flax and wheat [14-16]. It has many uses, including fuel, livestock bedding and fodder, thatching and basket-making. Straw are used as raw material in the production of thermal insulating fiberboards, reinforced thermoplastic composites and straw bales [17-22].

European houses built of straw or reeds are now over two hundred years old. In the United States, too, people turned to straw houses, particularly after the hay/straw baler entered common usage in the 1890s. Homesteaders in the northwestern Nebraska "Sandhills" area, for example, turned to baled-hay construction, in response to a shortage of trees for lumber. Bale construction was used for homes, farm buildings, churches, schools, offices, and grocery stores [23, 24].

The aim of the present study was to determine rational density of triticale straw for production of straw panels. As main parameter thermal conductivity was used. Moisture regime was evaluated by water vapour permeability and water absorption parameters.

II. MATERIALS AND METHODS

In tests triticale straw were used. In order to analyse macro structure of straw, specimens with density range from 60 kg/m^3 to 180 kg/m^3, were prepared. The samples were inspected by Digital camera Nikon „COOLPIX P90" with ×24 enlargement and resolution – 12.1Mpix.Straw parameters were determined usingcomputerized image processing and analysis program ImageTool.

Thermal conductivity tests were carried out by guarded hot plate apparatus λ-Meter EP 500 with additional protective heating rings and cooling ring according to (ISO 8302). Thermal conductivity measurements were carried out at mean temperature of 10 ºC and temperature difference through specimen of 10 °C. All specimens were conditioned at constant climate conditions (23±2) °C and (50±5)%.

The water vapour permeability studies were conducted in accordance with EN 12086 standard. During the test in a chamber and in the test dishes respectively 50% and 95% RH and 23° C temperature conditions were maintained.

Capillary absorption coefficient of $C_{w,s}$, g/(m^2·s) was determined in accordance with EN 772-11. Insulation composite samples were soaked for 90 min., recording the change in mass every 10 minutes.

Short-term water absorption was determined according to standard EN 1609: 2013, method A. Water absorption of the samples was determined after 48 hours. Intermediate weighing after 10 minutes, 1.5, 3, 6 and 24 hours were performed.

III. RESULTS

3.1. Macrostructure

View of specimens for macrostructure analysis is presented in Fig. 1. All specimens are characterised by different voids between the stalks and compression of straw stem. In Fig. 1a all straw stems are laid out freely – without compression signs. With increase of loading (Fig. 1b) macrostructure of straw infill gets a form – vertically and horizontally oriented straw, their form and size became more visible and form of spaces betweenstraw stems may be evaluated. Changes of straw form are not visible. When density reaches140 kg/m^3

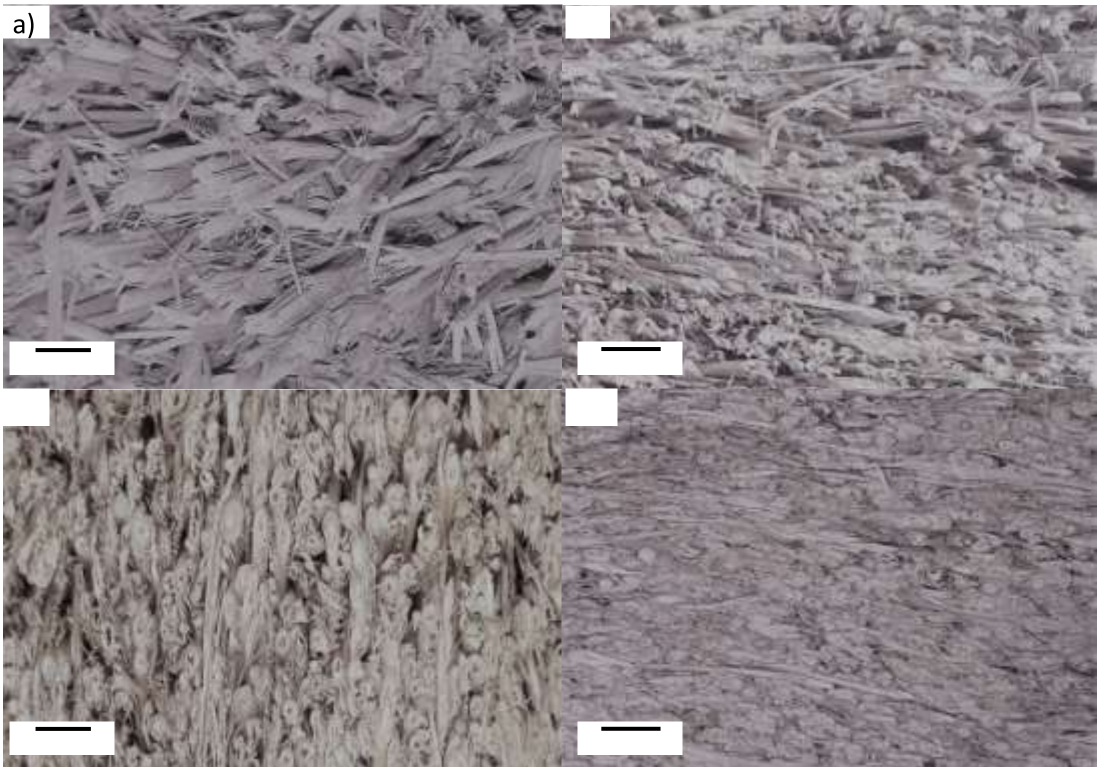

Fig. 1. Macrostructure of triticale straw, when density of specimens, kg/m^3: a – 60; b – 100; c – 140; d – 180

(Fig.1c), no significant changes in macrostructure of straw stems are observed. Voids between straw steams become smaller and separate straw stems start to deform. Significant changes are observed when density of straw infill reaches 180 kg/m^3. At such density macrostructure of straw infill looks as homogeneous product – without voids between straw stems, all straw are deformed and good contact between straw stem walls created. Attention should be paid to the fact that with increasing density of the specimens, mechanical treatment options are improved. As it is seen in Fig. 1, at low density (Fig. 1a) the surface of straw specimen is rough and at high density – smooth (Fig. 1d).As it is known, for plastering more suitable surface is rough.

3.2. Thermal conductivity

The results of thermal conductivity of measurement of triticale straw are presented in Fig. 2. Thermal conductivity of straw with densities range from 80 kg/m^3 to 190 kg/m^3 was analysed. For experiments panels with straw infill 500×500×100 mm were prepared. Processing of experimental data show that thermal conductivity values may be described by equation (1):

$$\overline{\lambda}_{10\,^\circ C} = -0.00155 + 0.000357 \cdot \rho + \frac{3.381}{\rho}, \quad (1)$$

where ρ is density of straw infill in kg/m^3. Mean square deviation is $S_r = 0.00364$ W/(m·K) ($n = 17$, square correlation coefficient $R^2_{\lambda \cdot \rho} = 0.682$). Graphical interpretation according to equation (1) is presented in Fig 2.

In addition the possible value of error $\delta = t_\alpha \cdot S_r = 0.00488$ (Fig. 1,dotted line)with probability (1−α)=0.9 is presented for regressionequation (2) which enables to pass on to interval prediction according to the following formula:

$$\lambda^{pred.}_{10\,^\circ C} = \overline{\lambda}_{10\,^\circ C} + \delta \quad (2)$$

where$t_{\alpha;f}$ is Student's criterion ($n = 17$ and $t_\alpha = 1.34$);S_r is standard deviation.

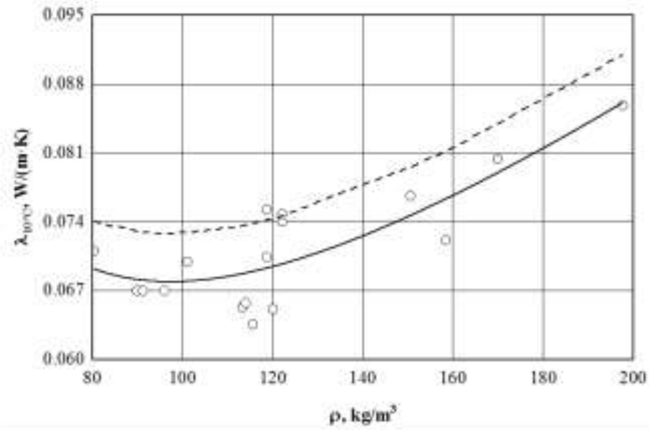

Fig. 2. Dependenceof thermal conductivity on the density of straw stems: solid line - regression line according to equation (1); the dotted line - predictive lineaccording to equation (2)

The lowest thermal conductivity of straw is observed at densities range from 80 kg/m^3 to 120 kg/m^3.From the density 120 kg/m^3 starts intensive increase of thermal conductivity values. It is related with a strengthening of the contact zones between straw stems and heat transfer by solid carcass. It should be noted that at the low-density straw is unstable – bad fixation in a wooden frame is observed. This phenomenon is observed till straw infill density reaches ~100 kg/m^3, i.e. while straw stems start to deform.

3.3. Water vapour permeability

Water vapour permeability of straw infill was expressed by water vapour diffusion resistance factorμ. Graphical interpretation of test results is presented in Fig. 3.

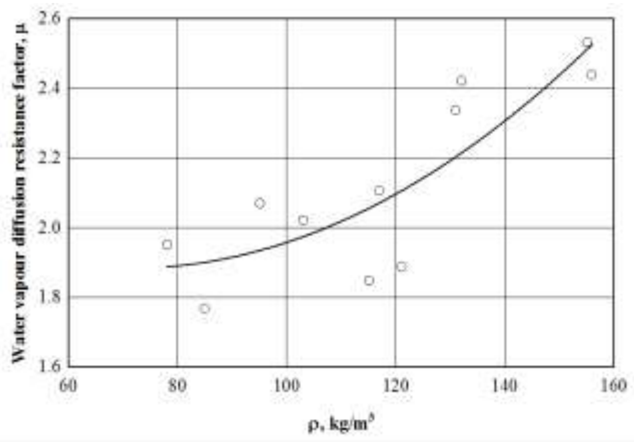

Fig. 3. Dependence of water vapourdiffusion resistance factor on the density of straw infill, kg/m^3

Dependence of water vapour diffusion resistance factor on the density, kg/m^3, can be approximated by regression equation (Fig. 3):

$$\mu = 2.335 - 0.0127 \cdot \rho + 0.0000892 \cdot \rho^2, \quad (3)$$

where standard deviation $S_r = 0.158$ ($n = 11$) andsquare correlation coefficient $R^2_{\mu \cdot \rho} = 0.713$.

As it is seen in Fig. 3, due to opportune macrostructure and microstructure as well [25]straw infill is characterised by good water vapour permeability. With increase of density water vapour permeability decrease, but values of water vapour diffusion resistance factor are much better than of other thermal insulating materials of similar density. Low water vapour diffusion resistance factorprovides good hydrothermal regime inbuilding envelopes.

3.4. Water absorption due to capillary action

Short-term water impact on straw was evaluated by capillary absorption coefficient. The dependence of capillary absorption coefficient of straw on the time and density is presented graphically in Fig. 4. Test results were fixed every ten minutes. Test results show, that largest capillary absorption coefficient is observed during first 10 minutes and very slow absorption during the remaining 80 minutes. It can be assumed that pores of straw stalks are filled by water in the first stage and during other stages of slow water suction to further straw stalk pores is observed. As it is stated in [26] cellulose based materials are characterised by high hygroscopic nature. The hygroscopicity is caused by the cellulose molecule itself, whereas the rate of water absorption is influenced by many parameters.

Forthedescriptionofcapillaryabsorptioncoefficientonthe bases oftestresultsmultiple regression equation (4) was obtained:

$$C_{w,s} = \exp \cdot \left(9.19 - 3.05 \cdot \ln T + 0.10 \cdot e^{-T}\right), \quad (4)$$

where mean square deviation is $S_r = 0.423$ g/(m^2·s) ($n = 108$) and square correlation coefficient $\eta^2_{L \cdot \rho} = 0.976$, whichshowsthatcapillaryabsorptioncoefficientby97.6% dependsonthetimeanddensityand just by2.4% - ontheotherfactors, whichhavenotbeendetermined.

3.5.Short term water absorption

Results of short term water absorption by partial immersion are presented in Fig. 5. As it is in Fig.5, water absorption process may be divided into two stages. First stage (duration about 10 hours) – fast water absorption at which end water absorption values reaches 60-80% by mass. Second stage – slow and uniform increase of water absorption values.

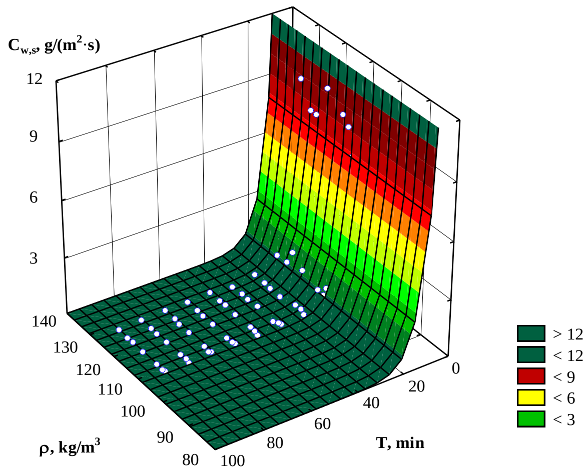

Fig. 4. Graphical interpretation of regression equation (4) of the dependence of capillary absorption coefficient of straw on the time *T*, min, and density ρ , kg/m^3

Dependence of water absorptionvalues W_τ , %, on straw infill density ρ , kg/m^3, and time T , hours, was approximated by regression equation:

$$W_\tau = 40.469 \cdot \left(T^{0.252} + 0.10 \cdot e^{-T}\right), \quad (5)$$

where mean square deviation is $S_r = 3.53$ % ($n = 96$) and square correlation coefficient $\eta^2_{L \cdot \rho} = 0.988$, which shows, that 98.8% water absorption values depend on the time and materials density.

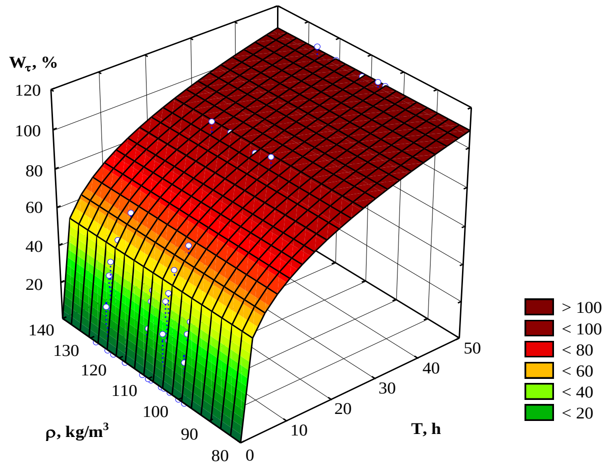

Fig. 5. Graphical interpretation of regression equation (5) of the dependence of short term water absorption of straw on the time *T*, min, and density ρ , kg/m^3

IV. CONCLUSIONS

Macrostructure analysis show that straw macrostructure control depends on compression level i.e. straw infill density. On the construction point of view the most suitable structure of straw is when the straw are compressed but separate air spaces between straw stalks are observed. To obtain such macrostructure, straw with a density of 100-120 kg/m^3 should be used.

Thermal conductivity of straw mostly depends on the density of material. The lowest thermal conductivity value of straw infill is at the densities range from 80kg/m^3 to 120 kg/m^3. At higher densities sudden increase of thermal conductivity values are observed.

Water vapour permeability is high at all density ranges and varies from 2.0 to 2.5. Dependence of water vapour permeability on straw density was obtained, but such characteristics as micro- and macrostructure, hygroscopic nature must be analysed every time too.

Capillary absorption coefficient shows very high water absorption at initial stage and slow water absorption at further stage. It can be assumed that pores of straw stalks are filled by water in the first stage and during other stages of slow water suction to further straw stalk pores is observed.

Analysis of results of short term water absorption show that 60-80% by weight straw absorbs during the first 10 hours. At a later stage, a slow increase of water absorption values of straw may be related to the eliminationof remaining air from the structure of straw infill.

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