Environment. Technology. Resources, Rezekne, Latvia
Proceedings of the 10th International Scientific and Practical Conference. Volume I, 61-66

Thermal Conductivity of Hemp Based Boards

Edgars Kirilovs[1], Silvija Kukle[2], Dana Beļakova[3], Anatolijs Borodiņecs[4], Ādolfs Ruciņš[5], Veneranda Stramkale[6]
[1,2,3,4] Riga Technical University, [5]Research Institute of Agricultural Machinery, [6]Agriculture Science Center of Latgale

Abstract. **Energy and raw material costs, an increase in environmental pollution, greenhouse gas emissions, global warming, depletion of fossil raw materials stimulate to seek and study alternatives to the synthetic fibers and products made of them for full or partial replacement. Renewable raw materials, including natural fiber sources, are the future of storage resources with a variety of positive effects on both the planet ecosystem and the living and working environment, and the energy consumption of delivering the required functionality. One of the most important energy-saving types is to reduce energy consumption in buildings by insulating them.**

For Latvian conditions suitable crops are historically grown flax and hemp. Within the framework of the studies, hemp stems are being used. Hemp compared with flax, are less suffering from diseases and less damaged by pests, so hemp cultivation is practically free from use of chemical pesticides and herbicides reducing the risk to the ecosystem.

One of the most frequently mentioned industrial hemp raw materials positive qualities are their very wide use, practically all plant parts can be used in production of different products. This work explores the possibilities and technologies within the Latvian grown hemp stems to work into board materials with insulation capability.

Hemp fibers/shives mix boards can fulfill the main function of insulation materials, i.e., to reduce the transmission of heat, because they have a porous structure and low density. Material thermal insulation properties affect physical and structural properties of compounds. Cost effective particles board samples from chopped hemp stems with three types of adhesives and different thicknesses were produced and their thermal conductivity evaluated. The technologies applied and test results will be discussed in the paper.

Keywords: **Hemp stems, insulation materials, particle boards, thermal conductivity.**

I INTRODUCTION

Insulating materials are used in public and private buildings, refrigerators, in insulating the electrical cables and in many other applications. Following the technology developments a range of new insulation materials are studied and technologies created. Around the world researches are carried out trying to find a thermal insulation material with excellent heat resistance, which at the same time also would be environmentally friendly, inexpensive, durable, easy to produce and use.

Flax and hemp bast fibres were applied for the insulation between the wood for centuries, but exactly in the last decades several types of insulation in form of roll materials are preferred instead of synthetic insulation. Despite the historical past, flax and hemp are often treated as a new material in heat insulation area. The contemporary studies of thermal qualities of bast fibres confirm their ability to compete with traditional insulation materials.

One of the reasons for usage is the higher price of bast fibres insulation in comparison with the price of wide used mineral wool. On the other hand, environmental performance of natural fibres insulation as low energy consumption for their production from annually renewable resources, CO_2 neutrality during the life cycle, the positive effect on the indoor air and potential for processing secondary raw material are positive, but not always supporting arguments.

This study presents experimental work done to produce thermal insulation materials from hemp stems harvested and chopped on the field with the following preservation like a silage [1; 2; 3; 4; 5]. Hemp plant particles are created the porous layer rich in air. Attention is attached to the thermal and acoustic qualities of this material, as well as its ability to regulate the moisture inside the building - absorbing and/or releasing moisture in the air. Thermal conductivity determination and analysis of insulating properties of hemp particle boards with different thicknesses using as binders Phenol formaldehyde (PF) – Tembec 340 and Urea-formaldehyde (UF) – Kleberit 871.0 resins are discussed.

ISSN 1691-5402

DOI: http://dx.doi.org/10.17770/etr2015vol1.206

II MATERIALS AND METHODS

The sequence of hemp board making, binder usage and board thickness base

According to Leibniz-Institute for Agricultural Engineering Potsdam-Born (ATB) developed technology harvested and chopped whole hemp plants (seeds, leaves, fibres, shives) are wet preserved under anaerobic conditions [2]. The resulting acidity of the raw material is pH = 4.6 to 5.0. Dry and preserved component weight ratio is 1: 3; there is taken 2/3 preserved component and 1/3 dry component that are mixed manually. In order to obtain a homogeneous mixture of hemp structure, sewing is done. Raw material that is stored for 14 days and used to manufacture the boards; binders Phenol formaldehyde (PF) – Tembec 340 and Urea-formaldehyde (UF) – Kleberit 871.0 resins in amount 10 g kg^{-1} of mixture dry mass are used as the binders. To ensure optimal moisture the preserved material is mixed with dry hemp straw and processed with an extruder. Mixed and drayed material is divided into 5 kg units and it is mixed with glue and fleece is formed. The resulting fleece is pressed in the heated press to 130 degrees with holding time 1900 seconds fewer than 100 bar pressure (Table 1). Pressing resulted in the board with dimensions 300 x 300 mm (Figure 1) and different thickness sample which were tested according ISO 8301:1991[6] standard. The thermal insulation were manufactured in cooperation with Research Institute of Agricultural Machinery and tested with Riga Technical University Faculty of Civil Engineering with the thermal flow meter Laser Comp FOX 600.

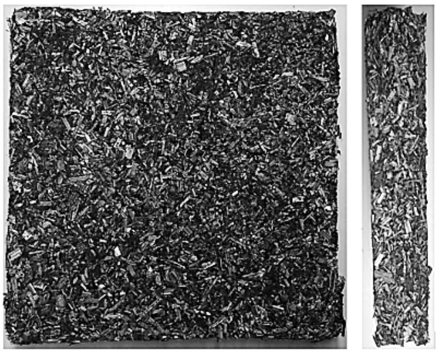

Fig.1. Board sample

Before starting the pressing (Figure 2) the upper and lower termoplates surfaces of the pressing chamber are heated to a temperature (T) and the moisture extraction is turned between pressing times (t_1) to (t_5). Pressing mode consists of five cycles (Table 1), each cycle consists of pressing time and the distance between the termoplates. In the first cycle the fleece material is pressed to a thickness (H_1) and kept (t_1) time. In the second cycle press is temporarily relieved for time (t_2) to remove the molded plates accumulated wet steam. In the third cycle the fleece material is compressed to a thickness (H_3) and kept (t_3) time. In the fourth cycle the press is relieved for time (t_4). In the fifth cycle the fleece material is compressed to a thickness (H_5) and kept (t_5) time. In the last cycle the steam from the molded plates is released most intensive, so after pressing (t_5) is continued 15 minutes moisture extraction.

Table 1.

Pressing mode

Pressing mode								
T, C°	1.stage		2.stage	3.stage		4.stage	5.stage	
	H_1, cm	t_1, sec	t_2, sec.	H_3, cm	t_3, sec.	t_4, sec	H_5, cm	t_5, sec.
130	20	30	20	11	30	20	10	1800
130	10	30	20	0.55	30	20	0.5	1800
130	0.64	30	20	0.35	30	20	0.32	1800
130	0.48	30	20	0.26	30	20	0.24	1800

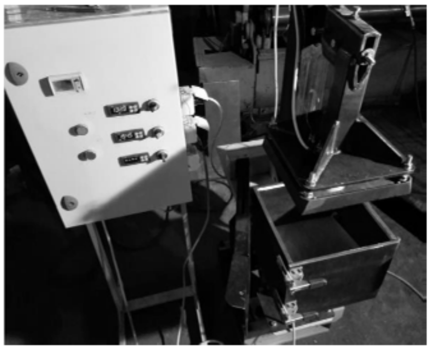

Fig.2. The technology of board pressing

Using PF binder the material's humidity must be in the ranges of 6 to 12%; if the moisture content is higher, partial or full curl is possible. To ensure that the glue hardens fast enough, pressing temperature must be maintained within the range of 140 to 150 °C. The pressing temperature can be technologically downgraded if the glue is mixed with hardener [7]. Using UF resin adhesive has a number of very good aspects: the low price, it is non-flammable, with bright colors and a very fast vulcanization. As negative features can be mentioned fact that the adhesive bond is not water resistant and formaldehyde can be released from the adhesive. [8]

Temperature is a very important factor that determines not only urea and formaldehyde reaction rate, but also the properties of the final product. If condensation occurs at temperatures lower than 60 °C, the result is low molecular weight compounds in water with poor adhesive properties. The reaction temperature of urea-formaldehyde resin extraction process is usually higher than 75 °C. With the amount of hardener can be adjusted both key settings: holding time and the time of using glue.[9]

The humidity of the glued material should not exceed 10 ± 2%. If the material humidity is higher, the connection strength is severely weakening. [10, 11]

Determination of the thermal conductivity coefficient using heat flow meter

Thermal conductivity is semi static process. In the calculations the temperature gradient is assumed constant. It is very difficult to accurately determine the thermal conductivity coefficient, because as soon there is change in temperature changes also the temperature gradient.

The thermal conductivity coefficient measuring equipment FOX600 is based on stationary heat flow generation, which passes through the samples of a specific thickness perpendicular to the largest sides.

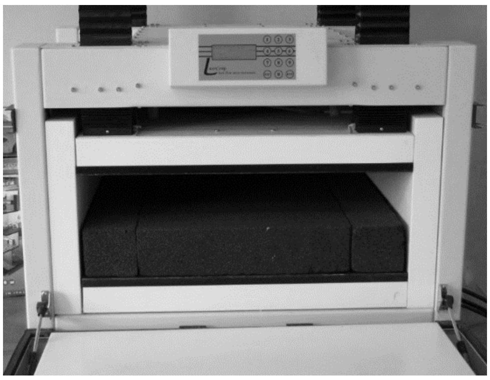

Fig. 3. Thermal conductivity measuring equipment FOX600 in RTU Faculty of Civil Engineering

Thermal conductivity measuring equipment FOX600 (Figure 3) technical data:

Thermal conductivity range 0.01-0.2 W/(m*K);
Accuracy 1%;
Maximum temperature of hot plate
(at 18^{o}C cooling water temperature) 65 °C
Maximum temperature of cold plate
(at 18^{o}C cooling water temperature) -10 °C
Temperature control stability ±0.03 °C
Thickness measurement precision ± 0.025 mm

Measured sample dimension:

- Maximum sample size 610 x 610 mm
- Minimum sample size 300 x 300 mm
- Maximum sample thickness 203 mm
- Actual measuring area 254 x 254 mm

Facility FOX600 heat flow meter operating principle has been established on Fourier -Bio one dimensional law. French mathematician and physicist Jean Baptiste Joseph Fourier and the French physicist and astronomer Jean-Baptiste Biot in 1822 created the law isotropic thermal conductivity environments. Fourier -Bio law links environmental temperature gradient with heat flux densities (1):

$$q = -\lambda \frac{dT}{dx} \frac{W}{m^2} \quad (1)$$

where: q – heat flux (heat quantity per unit time emitted through the isothermal surface with an area (S) through the sample, $\frac{W}{m^2}$;
λ – its thermal conductivity, $\frac{W}{m*K}$;
$\frac{dT}{dx}$ - temperature on the isothermal flat surface, $\frac{K}{m}$.

The heat emitted from warmer to colder material surfaces of the heat flux by body particle interaction. This contributes to body temperature equalization. Transferred heat amount- heat flux density is proportional to the temperature gradient, it is evaluated by the coefficient of thermal conductivity λ.

The temperature gradient can be determined by measurements of difference between temperatures of the hot and cold plates (2):

$$\Delta T = T_{hot} - T_{cold} , K \quad (2)$$

where: T_{hot} – hot plate temperature, K;
T_{cold} – cold plate temperature, K.

Average temperature gradient (3):

$$\frac{dT}{dx} = \frac{-\Delta T}{\Delta x}, \frac{K}{m} \quad (3)$$

where: ΔT – the difference between the hot and cold plate temperature, K;
Δx – sample thickness, m.

Before starting tests (by FOX600), the heat flow meter instrument must be calibrated using some certified sample (standard) having reliable known values of thermal conductivity $\lambda_{cal}(T)$.

Electric signal from the transducer Q (μV) is proportional to the heat flux q (4):

$$q = \lambda_{cal}(T_{cal}) * \frac{\Delta T_{cal}}{\Delta x_{cal}} = S_{cal}(T_{cal}) * Q, \frac{W}{m^2} \quad (4)$$

Where: $S_{cal}(T)$ – calibration factor;
Q – electric signal from the transducer, μV.

In order to obtain temperature dependent calibration is divided $S_{cal}(T)$ in parts. The calibration factor is measured in $\frac{W}{m^2*\mu V}$ or $\frac{W}{m^2*mV}$. Each of the two converters has its own temperature, and the calibration factors need to shift converter actual temperatures. The calibration factor' two separate sets have been measured during calibration.

The calibration factors S_{cal} (T) are the instrument's characteristics. They are used for thermal conductivity calculation during the test run (5):

$$\lambda_{test} = S_{cal}(T_{cal}) * Q * \frac{\Delta x_{test}}{\Delta T_{test}}, \frac{W}{m*K} \quad (5)$$

As each plate has its own temperature the calibration factors should be calculated for plate's actual temperature. Average of two thermal conductivity values is also the final result of thermal conductivity test.

Determination of heat diffusivity (6):

$$a = \frac{\lambda}{C_p*\rho}, \frac{m^2}{s} \quad (6)$$

where: $C_p * \rho$ – volumetric heat capacity, $\frac{J}{kg*K}$;

C_p – heat capacity in constant pressure, $\frac{J}{kg*K}$;

ρ – density, $\frac{kg}{m^3}$.

Thermal diffusivity coefficient's typical range for thermal insulation materials is approximately (4-7) $10^{-7}\,\frac{m^2}{s}$.

Fourier number (a dimensionless heat of similarity parameter that can be used in studying the problem of flow) can be determined (7):

$$F_0 = \frac{a*t}{(\frac{\Delta x}{2})^2} \quad (7)$$

where: a – temperature conductivity coefficient (physical value which characterizes the substance temperature changes (smoothing) the speed of unbalanced thermal processes) (8):

$$a = \frac{\lambda}{\rho*c}, \frac{m^2}{s} \quad (8)$$

where: λ – its thermal conductivity, $\frac{W}{m*K}$;

ρ – density, $\frac{kg}{m^3}$

c – heat capacity in constant pressure, $\frac{J}{kg*K}$

t – external conditions of the characteristic time, s;

$(\frac{\Delta x}{2})^2$ – characterized by body size, m^2.

The Fourier figure for FOX600 heat flow meter instruments constitutes -16 per hour 1 inch (25.4 mm) thick sample. Experiment showed that average value of two heat flow meters signals reaches equilibrium several times faster than their individual values. Therefore the duration of tests is shorter, because the value of thermal conductivity is calculated using the average value of the signal.

III RESULTS AND DISCUSSION

Thermal conductivity coefficient λ measurements of different thickness and density hemp boards

During the experiment there were obtained four sample variants with the arithmetical average thicknesses of 24, 32, 50 and 100 mm and the corresponding density of 243, 252 and 316 +/- 38 kg/m^3. Figure 4 shows that an increase in the thickness of the sample with UF binder in the range of 23 to 100 mm thermal conductivity of 0 °C side linearly increases in the range of 0.051 to 0.063 that is by 22.6% that is a large ratio. Changes under considered frequent intervals are showed by equation (9):

$$Y_{UF1} = 0.0475 + 0.0015X_b \quad (9)$$

where: X_b - sample thickness , mm;
determination coefficient 0.99

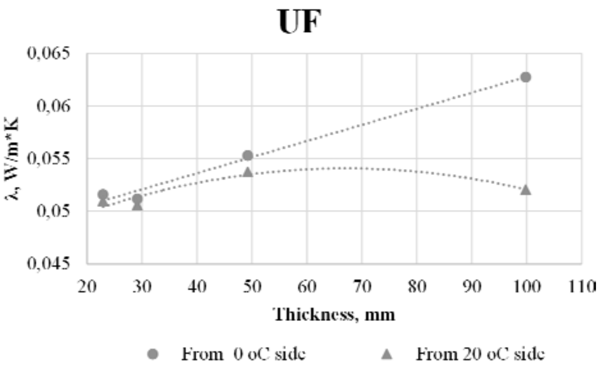

Fig. 4. The thermal conductivity of hemp fiber / shive insulation material with UF binder depending on the thickness of the sample

By contrast, the same coefficient of thermal conductivity of the sample at 20 °C side varies nonlinearly in a narrower area, reflecting the change in the nature of equation (10) second-degree polynomial form. Overall, the viewed sample thermal conductivity coefficient changes from 20 °C side can be regarded as a minor, as the maximum observed differences are within the error limits (not more than 2.9%). Also, the coefficient of determination 0.83 shows that the thickness effect only partly has caused thermal conductivity coefficient changes.

$$Y_{UF2}=0.0457+0.0025X_b-0.0002X_{b2} \quad (10)$$

Two times sieved by PF glue-related hemp fiber / shive insulation boards sample insulation coefficient varies nonlinearly in both tests from 0 °C side, and from 20 °C side (equations 11 and 12). In Figure 5 we can see that if the sample thickness changes in the range of 28 to 53 mm then thermal conductivity coefficients practically do not depend on whether the scale is from 0 °C or 20 °C side, as well as changes in thickness in the mentioned range have not effected the thermal conductivity coefficient values. However, reaching a thickness of 95 mm thermal conductivity coefficient values are increasing in both measurements, as well substantially are increasing differences in λ measurements: measured from 20 °C side the resulting coefficient by 21% in exceeds the one from 0 °C side resulting thermal conductivity coefficient presenting the opposite trend compared with UF adhesive material identified trends.

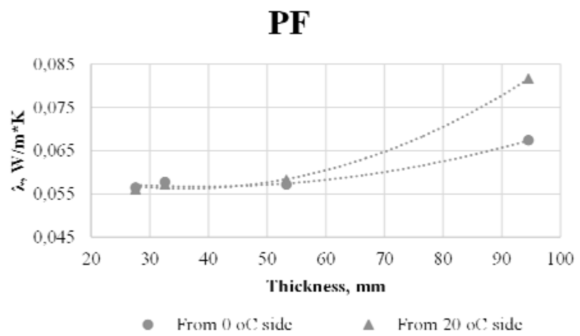

Fig 5. The thermal conductivity of hemp fiber / shive insulation material with PF binder depending on the thickness of the sample

$$Y_{PF1}=0.0618 -0.0026X_{b1}+0.0003X_{b12} \quad (11)$$

$$Y_{PF2}=0.0658-0.0053X_{b1}+0.0007X_{b12} \quad (12)$$

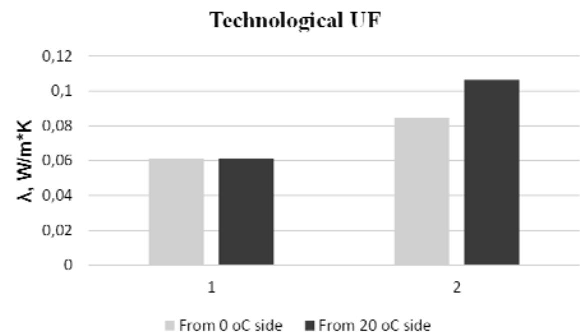

Fig. 6. The thermal conductivity coefficients of hemp fiber/shive fastened with technological UF glue. 1 - thickness 42.6 mm; 2 - thickness 104.2 mm

Comparing the graphs in Figure 6 shows that the small thickness sample values of the coefficient of thermal conductivity do not depend on what temperature is made the measurement, but by increase in thickness increases both the reference temperature and the effect of thickness. In the experiment by increasing thickness of 2.44 times the thermal conductivity coefficient increases 1.38 times from 0 °C side and 1.74 times from 20 °C side.

IV CONCLUSION

Although it is often considered that the thermal conductivity does not depend on the thickness of the material, a number of research results have showed that increasing the thickness ratio λ becomes dependent on the thickness [12; 13]. At the same time, depending on the material and the structure of its constituent components originating, acquiring technology and binders used the link may be stronger or weaker. We cannot exclude also the impact of tested methods.

Comparing the obtained board thermal conductivity of some materials traditionally used (mineral wool from 0.033- 0.055, hardwood 0.16, softwood timber 0.12, wool felt 0.07, wood fiber insulation boards 0.04- 0.06), and taking into account that for materials with a thermal potential is deemed to be, the thermal conductivity coefficient λ in the range of 0.16 to 0035 [14].

From hemp straw chips with a relatively simple process obtained board sample corresponds to the thermal conductivity of insulation materials required. Developing a prototype technology it will be possible to reduce the thermal conductivity precisely dosing binder consumption and dissipation.

V ACKNOWLEDGMENTS

This research is co-financed by the ESF within the project „Development of innovative technologies for the accumulation and production of heating and cooling", project implementation agreement No. 2013/0064/1DP/1.1.1.2.0/13/APIA/VIAA/050.

VI REFERENCES

[1] Pecenka R., Furll C., Radosavljevic L. Processing of Wet Preserved Hemp to Fibre Boards in a Pilot Plant. Saskatoon, : SaskFlax, 2008. p. 75- 80. ISBN 978-0-9809664-0-4.

[2] Idler C., Pecenka R. Ensiling- a new practice for preservation of hemp. Gauta Instituto, 2007. p. 40-48. Vol. 39. ISSN 1392-1134.

[3] Idler C., u.c., Wet Processing of Hemp: An Overview. London: Taylor & Francis, 2011. p. 59-80. Vol. 8. ISSN 1544-0478.

[4] Kirilovs E., Gusovius H-J., Kukle S. Inovative MDF board material for furniture from hemp. Zadar: University of Zagreb Faculty of Textile Technology, 2012. p. 1641-1646. ISBN 978-953-7105-47-1.

[5] Kirilovs E., Kukle S., Gusovius H-J., „Wet-preserved hemp fibreboard properties improvement with veneering" Submitted for publication in conference: 4TH International advances in applied physic and materials science congress & exhibition, Oludeniz, Turkey, April 23-27, 2014

[6] ISO 8301:1991. Thermal insulation; Determination of steady-state thermal resistance and related properties; Heat flow meter apparatus.

[7] Atta-Obeng E. Characterization of Phenol Formaldehyde Adhesive and Adhesive-Wood Particle Composites Reinforced with Microcrystalline Cellulose// Doctoral Thesis. - Auburn: Auburn University, 2011.

[8] Нуч В. Деревообработка. - Москова: Техносфера, 2008. стр. 129-143. ISBN: 978-5-94836-139-0

[9] Conner H. Urea-formaldehyde adhesive resins. [book author] Salamone J-C. Polymeric materials encyclopedia. USA: CRC Press, 1996, p. 8497-8501.

[10] Gierenz G.,Karmann W. Adhesives and Adhesives tapes. - Germany: Wiley-vch Verlag GmbH, 2001. p. 58-64. ISBN 3-527-30110-0.

[11] Pizzi A., Mittal K.L. Handbook of Adhesive technology. - New York: CRC Press; 2 edition, 2003. ISBN 1-40-8247-0986-1.

[12] Kirilovs E. *Efficient Use of Annually Renewable Raw Materials for Production of Fiber Boards and Composites.* Latvia : Institute of design technology, Department of material technology and design, 2013. Doctoral Thesis.

[13] Freivalde L. *Technology Impact on Hemp Fiber Insulation Material Properties.* Latvia : Institute of design technology, Department of material technology and design, 2014. Doctoral Thesis.

[14] Thermal Conductivity of some common Materials. [Online] Available from http://www.engineeringtooņepju lbox.com.