MATERIALE DE CONSTRUCȚII TRADIȚIONALE PENTRU IZOLAREA TERMICĂ DURABILĂ A ELEMENTELOR DE CONSTRUCȚII
TRADITIONAL BUILDING MATERIALS FOR SUSTAINABLE THERMAL INSULATING OF BUILDING ELEMENTS

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The construction industry uses an ever-increasing amount of thermal insulation materials to meet the building sector's growing energy efficiency demands. Exclusive use of synthetic thermal insulation may lead to a complicated process of re-integrate demolition waste in the economy and potential environmental damage over time. The use of traditional natural materials is ecological and through an appropriate design of the buildings, it offers efficient construction elements. This paper attempts to increase the professionals' awareness of some typical industry by-products (straw, sawdust, cellulose), with thermophysical characteristics interesting for the building sector. Besides the information needed for the usual engineering calculation, like thermal conductivity coefficient, we measured data needed for dynamic building simulation, such as thermal diffusivity, volumetric heat capacity, and specific heat capacity.

Industria construcțiilor folosește o cantitate din ce în ce mai mare de materiale de izolare termică pentru a satisface cerințele tot mai mari de eficiență energetică din sectorul construcțiilor. Utilizarea exclusivă a izolației termice sintetice poate duce la un proces complicat de reintegrare a deșeurilor din demolări în economie și potențiale daune mediului în timp. Utilizarea materialelor naturale tradiționale este ecologică și printr-un design adecvat al clădirilor, oferă elemente de construcție eficiente. Această lucrare încearcă să sporească gradul de conștientizare al profesioniștilor asupra unor subproduse tipice din industrie (paie, rumeguș, celuloză), cu caracteristici termo-fizice interesante pentru sectorul construcțiilor. Pe lângă informațiile necesare pentru calcule inginerești obișnuite, cum ar fi coeficientul de conductivitate termică, am măsurat datele necesare pentru simularea dinamică a clădirii, cum ar fi difuzivitatea termică, capacitatea termică volumetrică și căldura specifică masică.

Keywords: *thermal insulation; by-products; sustainability; building materials; sustainable buildings.*

1.Introduction

Building energy efficiency is a modern syntagm for an ancient concern. Humans in need for shelters relatively quickly identified the benefits of using thermal insulation materials. More than 3000 years ago straw-reinforced clay was used to build walls [1]. Depending on availability, different materials from natural sources, like bagasse, coconut, corn cob and pith, cotton, palm, hemp, reed, straw, sunflower, wood [2,3] were used as thermal insulation, and some of them are currently researched for the use in modern building insulation products [4-11]. The function of thermal insulation is to diminish the heat transfer through building elements. The main property of such a material is a low thermal conductivity [12].

Any product that significantly reduces heat flow through the building envelope, having a major impact on energy consumption [13], will save, during the lifetime of the building, more energy than it requires for its manufacture. [14]. As the demand for energy-efficient buildings increase, so is the use of thermal insulation materials. Long-term, the increase in building insulation will diminish the energy consumption and global warming potential gases. Nevertheless, these materials are produced right now, using fossil fuels and non-renewable materials, so for the moment this approach could even increase the problem. A couple of existing researches show the high embedded energy of conventional insulation materials like extruded polystyrene, expanded polystyrene, expanded polyurethane and mineral wool. This is between 118.67 ÷ 229.02 MJ_{eq} per functional unit (f.u) and high global warming potential in the range of 5.05 ÷ 13.22 kg CO_{2eq} per f.u. [15-17]. The functional unit is defined as the mass of insulation (in kg) that provides a thermal resistance of 1 [$m^2 \cdot K/W$] [18]. It is clear now that a considerable amount of energy and global warming potential is embedded in conventional insulation, as highly efficient buildings usually have R-values for building elements above 3 [$m^2 \cdot K/W$], with the insulation thickness between 10 ÷ 40 cm.

Analysing a single-family passive house, Beck [19] concludes that if polystyrene is used, the amount of embedded energy would be enough to heat this particular house for ten to fifteen years. A recently published book [20] uses the reference buildings for Romania to calculate the energy performance of buildings. It estimates that the embedded energy in thermal rehabilitated buildings is the equivalent of twenty years of operational

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energy, needed by those buildings to ensure thermal comfort. This corresponds to approximate six years of operational energy for the initial buildings.

For sustainable thermal insulating building elements, we consider it useful to give special attention to materials that embed a high percentage of by-products and require less energy for production. The use of by-products for the manufacture of building materials is an effective way to reduce the consumption of material resources and, therefore, to significantly decrease the environmental impact [21]. With an appropriate building design, using loose-fill insulation we can create high-efficiency building elements with relatively low costs. That is because unlike other building materials, bulk insulation could be quite affordable, for example, when using the by-products of other industries. Insulating natural raw materials have had a growing market share between 1995 ÷ 2010 [22] and this trend is expected to continue in developed countries, as environmental awareness increases. However, these products are still only marginally used, having less market share, in other countries. The renewable alternative represents less than 2% of the market [23] in Spain. In the present economic climate, customer demand for low-carbon housing integrating industry by-products is still limited, but it is anticipated that low-carbon housing will be a growing market in the near future [24÷26]. As Sodagar [24] estimates, around six tons of CO_2 are sequestered by straw as biotic material in a standard semi-detached, two-story and three-bedroomed house, with gross area of 85.75 m^2. Moreover, another nine tones are stored as wood and wood products. Therefore, the carbon lock-up potential of such innovative designs making use of renewable construction materials is suggested to reduce the case study house's whole-life CO_2 emissions over its 60-year design life by 61% compared with a similar house made from usual materials [24].

A paradigm shift to the last hundred years building system is necessary as using low-cost / low-energy natural materials is environmentally friendly. A dedicated building design, developed from scratch considering the advantages/disadvantages of raw materials, can create high-efficiency construction elements. In practice, we should implement more building elements and building execution details achievable with high usage of traditional bulk materials like straw, recycled cellulose, sawdust. In this context, this paper investigates the thermal conductivity of finely chopped straws, coarsely chopped straws, two types of sawdust, and a by-product consisting of fine shredded thin paper and cellulose, originating from the tobacco industry.

2. Materials and methods

2.1 Materials

All the tested materials came from local industries in Romania, and they were provided in different batches. To test relevant samples, special attention was accorded to use clean materials, mainly without inclusions of sand, dirt, or dust that would introduce a deviation impossible to quantify in the absence of the values for the uncontaminated materials. The contamination of samples would be a disruptive factor, changing their thermal properties regardless the process of conditioning them at constant mass. This may explain, at least partially, the substantial discrepancies between results from the reviewed literature, especially regarding straw thermal conductivity coefficient [27,28], so we documented the probes with relevant images. Moreover, knowing the properties of uncontaminated materials, the quality of raw materials could be assessed.

The products tested in this study are:

- finely chopped straws (Fig. 1), an agricultural waste from the Triticale family, having the stem cleaned from impurities like dust or dirt and partially broken as a result of an intense mechanically process which is necessary to cut the straws at lengths between 2 ÷ 5 cm;
- coarse cut straws (Fig. 2), which are from the same Triticale family, but from a different batch than finely chopped straws, without inclusion of parasitic weeds. The coarse cut straws are less processed, with a length between 10 ÷ 15 cm and a relatively intact stem.
- fine sawdust (Fig. 3) from softwoods like firs (genus Abies), pine (genus Pinus) or spruce (genus Picea), currently a by-product of sawmills;
- wood shavings (Fig. 4) from softwoods, currently a by-product of woodworking;
- cellulose (Fig. 4) could be a by-product of different industries. Particularly for this research, we used a product that is considered waste by the tobacco industry, consisting mostly from cellulose acetate (from shattered cigarette filters) and a low percentage of fine shredded thin cigarette paper.

2.2 Methods

2.2.1. Measuring the steady-state thermal properties (R-value, thermal conductivity)

For engineering purposes, the determination of thermal conductivity coefficient values is realized under strict regulations [29], in order to assure similar values when the tests are reproduced with different equipment, personnel and laboratories.

The steady-state tests performed to measure the thermal conductivity of the samples were carried out using the guarded hot plate method (GHP), a technique that it is used since 1989 in different forms, it is well established and documented in [29].

Fig. 1 - Finely chopped straws in testing frame
Paie tăiate fin în cadrul de testare

Fig. 2 - Coarse cut straws in testing frame
Paie tăiate grosier în cadrul de testare

Fig. 3 - Fine sawdust (front) and softwood shavings (back)
Rumeguș fin (față) și așchii de rășinoase (spate)

Fig. 4 - Cellulose in testing frame
Celuloză în cadrul de testare

For the results to be more relevant for practical applications, we choose to follow the conditioning procedure specified by the European assessment document relevant for thermal insulation products made of vegetable fibres [30]. The materials were conditioned to dryness for 72 hours at (70 ±2) °C in a Venticell 22 laboratory oven, with air taken at (23 ± 2) °C and (50 ± 5) % relative humidity.

To determine the thermal resistance of loose-fill materials, they are encased within a sample frame, which is introduced in GHP equipment. The sample frame consists of thermal insulation material all-round, occasionally up to the GHP edges. This sample frame maintains the proper shape of the material when testing, which is mandatory. It also shields the sample from the laboratory air, reducing heat and mass transfer in the horizontal plane to almost zero. The frame is designed to stand in the guarded area of the equipment to not interfere with the central surface (where thermal properties are determined). For loose-fill materials, polyurethane (PUR) or extruded polystyrene (XPS) frames are usually provided (Fig. 4). These frames have the advantage of high-water vapour resistance and, over time, better resistance to usual laboratory wear. Without significant thermal mass, one test could take only a couple of hours for these samples. All this time, the material is tightly encased, as it is placed in the frame that shields it laterally and between the aluminium testing plates (the upper and lower part of the material) (fig. 4). The measuring method is according to the specifications of [29] and was previously described in the scientific literature.

We first tested the products at the density at which they settled under their own weight, then repeated the test at the maximum density we could achieve in the laboratory, specifically, at the maximum pressure the GHP equipment could produce. All the tests were realized over a temperature interval to show the material's dependence with the mean temperature of the specimen.

2.2.2. Method for thermodynamic properties (thermal diffusivity, specific heat capacity)

Dynamic simulations of buildings are required to determine the heating, cooling demand and energy performance, especially in the case of very efficient buildings [31]. These simulations demonstrate the insulation and thermal mass impact, assess the risk for overheating when the air conditioning units malfunction [32], and the building system's operation mode, overall. In order to include natural materials in building dynamic simulation, we need to know thermal characteristics like thermal diffusivity, volumetric heat capacity, specific heat capacity. There are means to determine these properties using GHP with additionally flux-meter pads [33]. However, for this research, we used a commercially available equipment, based on Transient Line Source (TLS) method. The materials were tested when in thermodynamic equilibrium with the ambient atmosphere at 24°C and 45% relative humidity, at normal pressure. The materials were introduced into cylindrical PET specimens, with the height of 19 cm and 9 cm in diameter. The needle probe was vertically inserted in specimens, longitudinally on their central axis.

2.3 Equipment

2.3.1. Equipment for steady-state tests

We used two guarded hot plate (GHP) equipment to measure the thermal conductivity coefficient. One of them is ANTER UNITHERM 6000, which is a fully automated operation GHP, designed for insulating materials. It has the cold isothermal plate at the superior side of the sample and is designed to measure the thermal resistance of specimens between - 30°C ÷ 650°C [34]. The thermal conductivity range is between 0.02 ÷ 2 W/m·K, the specimen is (300 × 300) mm, and the sample thickness is a maximum of 75 mm. The other GHP used for these measurements is λ-METER EP500e. This equipment is a state-of-the art GHP [35], fully automated, using modern technologies that provides the capability of testing without a chamber encasing the sample.

2.3.2. Equipment for dynamic tests

For the thermodynamic properties of specimens, a portable instrument for direct measurement of heat transfer properties was used. For this study we used the needle probe, which is best equipment sensor for testing non-consolidate and composite materials [36]. The measurement is based on analysis of the temperature response of the analysed material to heat flow impulses.

3. Results and discussions

3.1.Steady-state results

Under real conditions, the thermal conductivity of materials differs from the laboratory results. This is mainly due to a different temperature and humidity in an actual building envelope and discrepancies between materials preparation in the laboratory and their application in buildings.

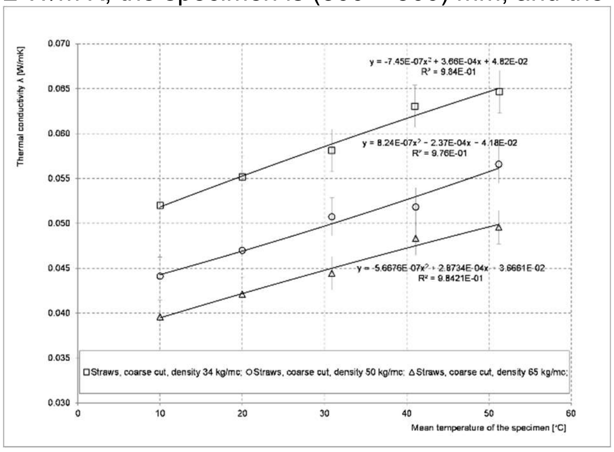

Fig. 5 - Test results and correlations for coarse cut straws
Rezultatele testelor și corelările pentru paie tăiate grosier

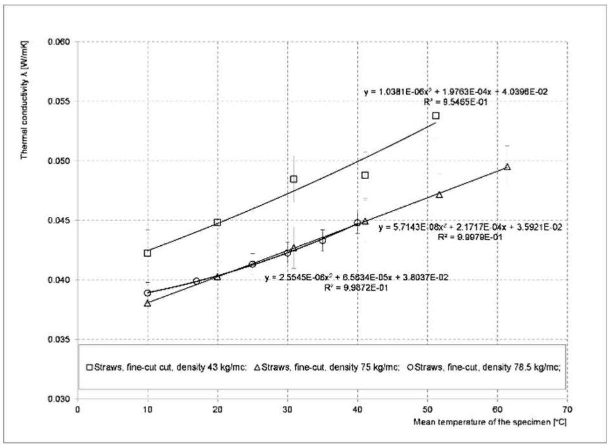

Fig. 6 - Test results and correlations for fine cut straws/
Rezultatele testelor și corelările pentru paie tăiate fin

Fig. 7 - Straws tested at 29 kg/m^3, perpendicular to heat flow/
Paie testate la 29 kg/m^3, perpendicular pe fluxul de căldură

Fig. 8 - Straws tested perpendicular to heat flow (a magnified picture)/
Paie testate perpendicular pe fluxul de căldură (o imagine mărită)

Fig. 9 - Finely cut straws. A magnified picture to present a closer look at the material/ *Paie tăiate fin. O imagine mărită pentru a prezenta o privire mai atentă asupra materialului.*

Moreover, depending on the geographical location of the building and the position in the building envelope, a layer of thermal insulation can operate at a different temperature regime, and this will influence its behavior. To assess this issue, the thermal conductivity coefficient (λ) of the selected materials was determined over a range of densities and temperatures between 10°C ÷ 50°C, as shown in Figures 5 to 9.

In the tested densities range, we confirm that for analysed samples the thermal conductivity value changes with an increase in density, as the air gaps volume is decreasing in the thermal insulation fabric, therefore the convective heat transfer is diminishing. Another relevant information is regarding the slope of the curves, as a product with higher air gaps volume is showing a high slope, meanwhile smaller and equally distributed pockets of air make the convective transfer relatively constant in the tested temperature interval.

The low thermal conductivity coefficients of the samples are a result of the porous macrostructure of the tested materials. Meanwhile, the cell's walls conductivity, which are made of vegetal fibers, is significantly higher. This is similar for wood by-products materials, as the thermal conductivity coefficient for wood cell wall substance at 0% moisture content is 0.410 W/m·K while lambda value for structural softwood lumber at 12% moisture content is (0.12 ± 0.02) W/m·K [37-39]. While this value is appropriate for the solid wood particles within the sample, the tested material has supplementary small pockets of air between these wood fragments, therefore a lower λ value.

3.1.1. Straw products

Finely cut straws compacted better under their own weight, therefore the samples using them were tested starting with the density of 43 kg/m^3, then raised to 75 kg/m^3 and 78.5 kg/m^3 resulting $\lambda_{10,\ dry}$ of 0.042 W/m·K, 0.0381 W/m·K and 0.0389 W/m·K respectively (Fig. 6). The settlement density for our samples made with coarse straws was 34 kg/m^3. After testing this first sample, we increased its density at 50 kg/m^3 and 65 kg/m^3 resulting $\lambda_{10,\ dry}$ of 0.052 W/m·K, 0.044 W/m·K and 0.040 W/m·K, respectively (Fig. 5).

The results obtained for fine-cut straws at $\rho \approx$ 75 kg/m^3 ($\lambda_{10,\ dry} \approx$ 0.039 W/m·K) is especially interesting. Previous tests, realized with the same equipment UNITHERM 6000, showed a $\lambda_{10,\ dry}$ of 0.057 W/m·K for straws manually arranged perpendicular to heat flow (Fig. 7), compacted at $\rho \approx$ 29 kg/m^3 [39] and this was considered consistent with similar findings, as tests performed for US standards give values of 0.046 W/m·K for straws perpendicular to heat flow, respective 0.061 W/m·K for straw running parallel to thermal flux [40]. Similar, [28] specify values between 0.04 ÷ 0.063 W/m·K for straws arranged in the same way, with densities of the samples between 50 ÷ 90 kg/m^3. Therefore, obtaining a thermal conductivity lower than for the straws perpendicular to heat flow is apparently a paradox. It is well known that thermal conductivity has a smaller value when heat flow is perpendicular to straw is less than in the case of thermal flux in the length of straws [28]. However, when the materials are closely observed, there are visible discrepancies between them (Fig. 8, 9). The whole straw has thicker, denser straws and permits significant air gaps between the individual straws (Fig. 8). Simultaneously, for the grounded straws (Fig. 9), the leaf and stems were broken down, shattered and are visible in the sample some finer stems, which appear to be from different weeds, parasitic plants of the crop. Overall, these components create to a greater extent an even structure, with fine particles partially filling the space between stems, thus with smaller air gaps, reducing the convection transfer and providing better thermal insulation. Comparable results were observed through literature, with thermal conductivity values of broken straws being lower than for the whole straws arranged perpendicular to heat flow [28].

For most research, though, straws' thermal conductivity is found between 0.04 ÷ 0.067 W/m·K, with slightly higher values (0.062 ÷ 0.07 W/m·K) when testing directly straw-bales [41]. The upper value of 0.067 W/m·K is provided by [42], testing a 60 kg/m^3 density straw-bale and it also provides useful data for dynamic simulations of building elements using straws. The result was obtained using a TLS equipment that is susceptible to be affected by sensor positioning, the mean temperature of the sample is not specified as well as the material conditioning procedure. Other research [28] presents a value of 0.092 W/m·K for a sample made from straw bales and 0.079 W/m·K for a sample made from straw roll, from a total of 10 samples tested.

3.1.2. Softwood products

Regarding the softwood by-products, the fine sawdust was the least compressible product

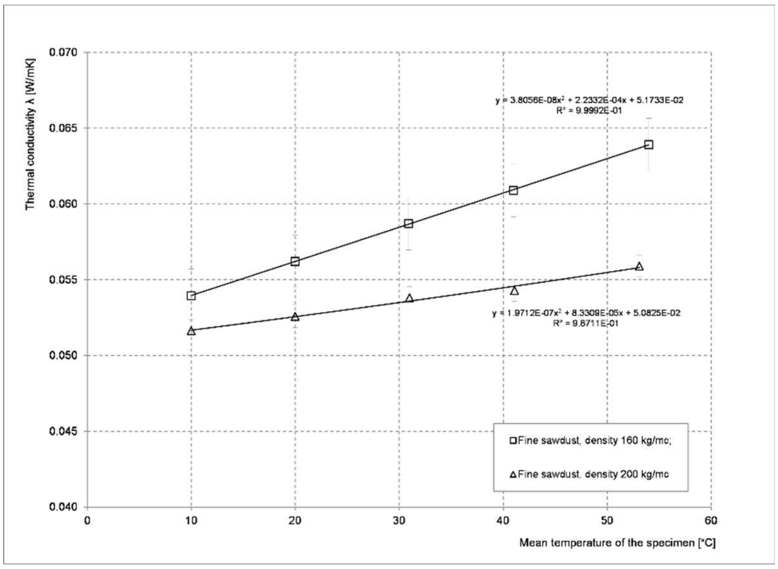

Fig. 10 - Test results and correlations for fine softwood`s sawdust/ *Rezultatele testelor și corelările pentru rumeguș fin de rășinoase*

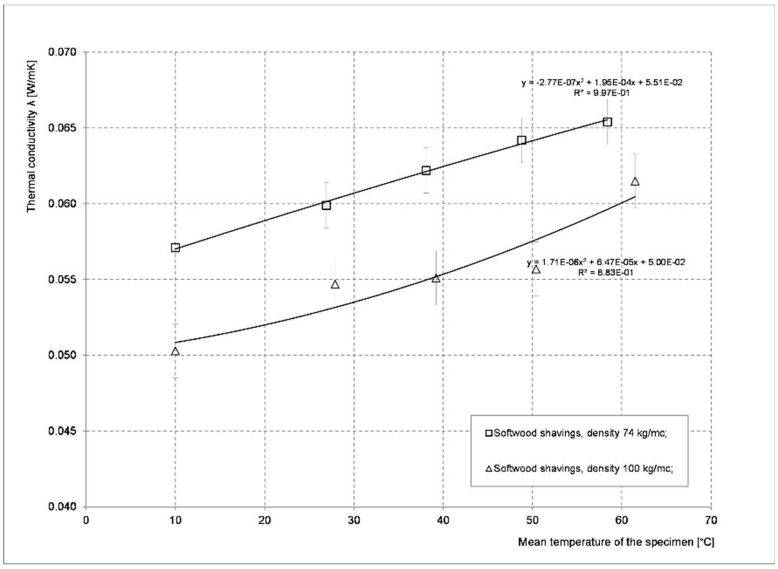

Fig. 11 - Test results and correlations for coarse softwood shavings/ *Rezultatele testelor și corelările pentru așchii de rășinoase grosiere*

tested. Under its own weight it compacted at 160 kg/m^3 resulting a sample with $\lambda_{10,\ dry}$ of 0.054 W/m·K. The density of the sample could be increased only by 25% in the laboratory, obtaining a sample with the density of 200 kg/m^3 that was characterized by a thermal conductivity $\lambda_{10,\ dry}$ of 0.052 W/m·K. Fig. 10 presents these values and the evolution of lambda (thermal conductivity coefficient) over a large temperature interval. Using softwood shavings, we could produce samples with the start-up density of 74 kg/m^3 (the settlement density for the tested material) and up to 100 kg/m^3 resulting $\lambda_{10,\ dry}$ of 0.057 W/m·K and 0.050 W/m·K (Fig. 11). The thermal conductivity coefficient of wood by-products is not as good as other materials could provide, but due to the air gaps between the wood fragments it is considerably lower than the original softwood lumber (approximate (0.12 ± 0.02) W/m·K [38].

A review of existing legislation regarding the recommended levels of thermal conductivities [14] show that in British Standards and Building Regulations, the recommended levels vary between 0.044 W/m·K and 0.037 W/m·K while in Asia, the Korea Industrial Standards specify a value less than 0.044W/m·K and the Taiwan Green Mark that λ must be less than 0.044 W/m·K. From this perspective, the softwood by-products fall short of classification as insulating materials. Nevertheless, this is relative as they could compensate by price and integrated into a 50 cm thick wall, which is usual for highly efficient buildings [43-45], would provide a U-value lower than 0.13 W/m^{2}K.

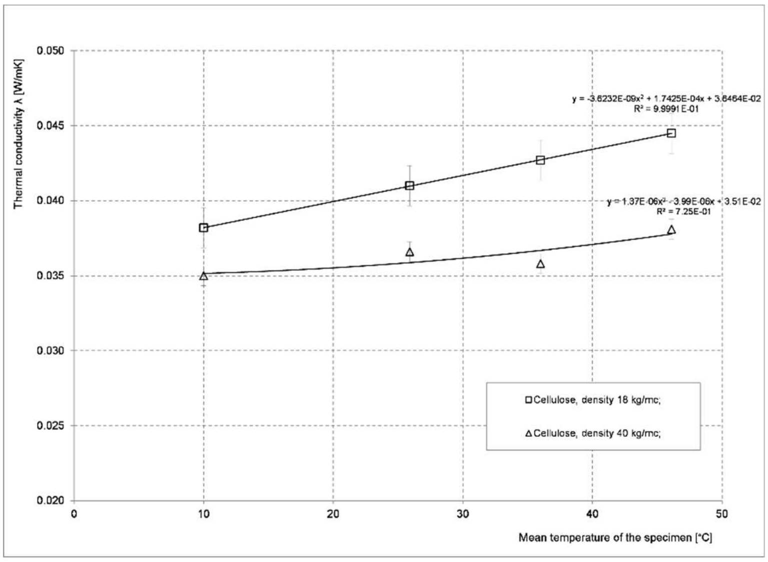

Fig. 12 - Test results and correlations for cellulose/ *Rezultatele testelor și corelărilor pentru celuloză*

Table 1

The measured thermodynamic properties of the materials/ *Proprietățile termodinamice măsurate ale materialelor*

	Density, [kg/m^3]	Diffusivity, [$\times 10^7 \cdot m^2 \cdot s^{-1}$]	Volumetric heat capacity, [$kJ \cdot m^{-3} \cdot K^{-1}$]	Specific heat capacity, [kJ/kg·K]
Finely chopped straws	43.77	5.79 (0.045)	94.02 (0.001)	2.15
Finely chopped straws	75.30	3.49 (0.009)	160.35 (0.001)	2.13
Coarse cut straws	48.25	6.71 (0.004)	94.96 (0.001)	1.97
Coarse cut straws	65.11	6.63 (0.109)	94.09 (0.001)	1.45
Coarse cut straws	70.45	3.81 (0.020)	153.32 (0.001)	2.18
Fine sawdust	163.70	2.89 (0.003)	202.87 (0.002)	1.24
Fine sawdust	200	2.77 (0.004)	220.61 (0.002)	1.10
Wood shavings	100	5.44 (0.019)	110.54 (0.001)	1.11
Wood shavings	120.87	4.74 (0.005)	134.32 (0.001)	1.11
Cellulose	40	6.44 (0.002)	67.93 (0.001)	1.70

The values inside the parentheses are standard deviation of measured values.

3.1.3. Cellulose

The tested cellulose-based material, consisting of cellulose acetate and a small percentage of shredded cigarette paper, compacted very well, resulting in samples with small air gaps, evenly distributed in the volume of the material. Using cellulose, we produce a sample with the lowest density possible of 18 kg/m^3 and one with a density of 40 kg/m^3. Both samples provide excellent results in terms of thermal conductivity, with a thermal conductivity coefficient $\lambda_{10,\ dry}$ of 0.038 W/m·K for the low-density sample, respectively 0.035 W/m·K for the high-density sample. Plotting lambda as a function of mean specimen temperature (Fig. 12) shows that cellulose is uniformly compacting, with insignificant air gaps, which results in a reduced convective heat transfer in the material's pores and a relatively low variation of lambda values over the analysed temperature interval.

3.2.Dynamically measured thermophysical properties

Table 1 shows the measured values of the density, thermal diffusivity and volumetric heat capacity of the samples tested using the transient line source equipment. Knowing these parameters, the specific heat capacity was calculated. We tested each sample multiple times to minimise possible errors. The equipment automatically calculates the standard deviation (SD) as an indicator of measured data dispersion, and test could be finished when obtaining a low value for SD. (Explanation/completion: However, this data is not exported from equipment. To confirm the test relevance, we calculated SD in Microsoft Excel, using the implemented STDEV.S. This function calculates SD using the "n-1" method. The values confirm a quite small dispersion relative to the average data and are presented in Table 1, in the parentheses following the average value).

These data are required for solving the heat equation for dynamic building simulations or thermal behaviour of building elements [46]. The main information sources are [47] and [48]. For materials relatively close to those presented in this paper, [47] provides information regarding plates from straw/hemp/reed (specific heat capacity c_p 1.67 kJ/kg·K) and wood/wood products (c_p 2.51 kJ/kg·K) while [48] give data referring to wood (c_p 1,60 kJ/kg·K) and OSB(oriented strand board)/MDF(medium density fibreboard) panels

(c_p 1.70 kJ/kg·K). The measured data for straws (c_p 1.45÷2,18 kJ/kg·K) and cellulose (c_p 1.70 kJ/kg·K) came close to those provided by these two information sources for wood products (c_p 1,60 - 2,51 kJ/kg·K), but provides additional information in terms of discretization. Meanwhile, the wood shavings results (c_p 1.11 kJ/kg·K) significantly differ from those for OSB (c_p 1.70 kJ/kg·K), implying the resins used in OSB production, which considerably changes the thermal behaviour.

4. Conclusions

Thermal insulation is an important element in the building sector, as it reduces the energy demand, increase the interior temperature of the construction elements in contact with the outdoors and increase thermal comfort.

As energy efficiency increases, the operational energy of the building is lower, so it is the CO_2 footprint. Long-term, the increase in building insulation will significantly reduce the energy consumption and global warming potential gases. Unlike other building materials, loose-fill insulation usually embed less energy and it could be quite affordable, if using the by-products of other industries. Four materials (finely chopped straws, coarse cut straws, fine sawdust, wood shavings and cellulose) were tested at different densities, over an interval of mean temperatures of samples. In order to provide useful data for building engineering sector, the material conditioning and testing was carried in accordance with [30]. The results were provided by GHP equipment, according with [29], for steady-state heat transfer. Moreover, for dynamical simulation, the article provides useful data as diffusivity and heat capacity of these thermal insulators.

Among the tested materials, softwood by-products had the higher values for the thermal conductivity coefficients, as the best value was $\lambda_{10,\,dry}$ 0.050 W/m·K, obtained for wood shavings compacted at 100 kg/m^3, while fine sawdust recorded a conductivity $\lambda_{10,\,dry} \in [0.052 \div 0.054]$ W/m·K. However, this value is reasonably lower than thermal conductivity of softwood lumber. Moreover, the fine sawdust showed a low settlement in time, which is interesting from the engineering point of view, for a loose-fill insulation material.

Straw materials show good insulation properties, with $\lambda_{10,\,dry} \in [0.040 \div 0.052]$ W/m·K for the coarse cut straws and $\lambda_{10,\,dry} \in [0.0381 \div 0.042]$ W/m·K for finely grounded straws. Remarkably, values for finely grounded straws are significantly lower than those mentioned by scientific literature for straw perpendicular to heat flow. It is showed that finely grounded straws, with shattered leaves and stems, create an entirely different material, with an appearance and thermal behaviour more related to cellulose than to straws. This setup has fine particles partially filling the spaces between stems, thus limiting heat transfer through convection. Also, the broken stems have thinner walls, implying a reduced conductivity.

The cellulose acetate showed the best thermal insulating properties from the tested materials, with $\lambda_{10,\,dry} \in [0.035 \div 0.038]$ W/m·K, some values being better than entry-level conventional thermal insulators. It compacted very well, creating an insulator with small air gap volumes, with a thermal conductivity coefficient relatively constant over the tested temperature interval.

Regarding straws, a problem is the significant differences between the tested materials, and this implies there is a difficult task to standardize straws as a building material. For the moment, the recommendation is that every batch should be individually evaluated before use, meanwhile we continue the researches in this area.

REFERENCES

[1] I. Spiridon, I. Natural fiber-polyolefin composites. Mini-review. Cellul. Chem. Technol, 2014, **48,** 599.

[2] F. Asdrubali, F. D'Alessandro, S. Schiavoni, A review of unconventional sustainable building insulation materials. Sustainable Materials and Technologies, 2015, **4**, 1.

[3] R. Stapulionienė, R. Tupčiauskas, S. Vaitkus, S. Vėjelis, Development and investigation of thermal insulation from hemp-polylactide fibres, Engineering Structures and Technologies, 2016, **8(1),** 23.

[4] M. E. Ali, A. Alabdulkarem, On thermal characteristics and microstructure of a new insulation material extracted from date palm trees surface fibers. Construction and Building Materials, 2017, **138**, 276.

[5] H. Binici, M. Eken, M. Kara, M. Dolaz, An environment-friendly thermal insulation material from sunflower stalk, textile waste and stubble fibers. In 2013 International Conference on Renewable Energy Research and Applications (ICRERA), p. 833.

[6] E. Latif, M.A. Ciupala, D.C. Wijeyesekera,, The comparative in situ hygrothermal performance of Hemp and Stone Wool insulations in vapour open timber frame wall panels. Construction and Building Materials, 2014, **73,** 205.

[7] S. Panyakaew, S. Fotios, New thermal insulation boards made from coconut husk and bagasse. Energy and buildings, 2011, **43(7),** 1732.

[8] X. Y. Zhou, F. Zheng, H. Li, G., C. L Lu, An environment-friendly thermal insulation material from cotton stalk fibers. Energy and Buildings, 2010, **42(7),** 1070.

[9] M. Palumbo, A.M. Lacasta, M.P. Giraldo, L. Haurie, E. Correal, Bio-based insulation materials and their hygrothermal performance in a building envelope system (ETICS), Energy and Buildings, 2018, **174,** 147

[10] Karatas, M. Z., Rizaoglu, T., Technical Characteristics of Building Isolation Plates Produced from Natural Materials Such as: Perlite, Pumice Micaschist and Arenitized Granite, Romanian Journal of Materials, 2017, **47(2)**, 244.

[11] Abdullah, A., Jamaludin, S. B., Noor, M. M., Hussin, K. Mechanical properties and fracture behaviour of coconut fibre-based green composites. Romanian Journal of Materials, 2011, **41(3)**, 262.

[12] B. P. Jelle, Traditional, state-of-the-art and future thermal building insulation materials and solutions–Properties, requirements and possibilities. Energy and buildings, 2011, **43(10),** 2549.

[13] L. Lei Zhang, Z. Deng, L. Liang, Y. Zhang, Q. Meng, J. Wang, M. Santamouris, Thermal behavior of a vertical green facade and its impact on the indoor and outdoor thermal environment. Energy and buildings, 2019, **204,** 109502.

[14] Procurement, Thermal insulation technical G. P. background report. Brussels: European Commission, 2010, 42.
[15] I.Z. Bribián, A.V. Capilla, A.A. Usón, Life cycle assessment of building materials: Comparative analysis of energy and environmental impacts and evaluation of the eco-efficiency improvement potential. Building and environment, 2011, **46(5),** 1133.
[16] P.Kosiński, P. Brzyski, H. Szewczyk, W. Motacki, Thermal Properties of Raw Hemp Fiber as a Loose-Fill Insulation Material, Journal of Natural Fibers, 2018, **15(5),** 717.
[17] S. Schiavoni, F. Bianchi, F. Asdrubali, Insulation materials for the building sector: A review and comparative analysis. Renewable and Sustainable Energy Reviews, 2016, **62,** 988.
[18] N. Pargana, M. D. Pinheiro, J. D Silvestre, J. de Brito, Comparative environmental life cycle assessment of thermal insulation materials of buildings. Energy and Buildings, 2014, **82**, 466.
[19] A. Beck, U. Heinemann, M. Reidinger,J. Fricke, J., Thermal transport in straw insulation. Journal of Thermal Envelope and Building Science, 2004, **27(3),** 227.
[20] D. Constantinescu, Tratat de inginerie termică - termotehnica în construcţii (Vol. 2) Conformarea energetică a clădirilor performante din punct de vedere energetic și al mediului natural. AGIR publisher, ISBN 978-973-720-789-0, 2020, 281.
[21] C. Aciu, N. Cobîrzan, Use of agricultural products and waste in the building materials industry, ProEnvironment/ProMediu, 2013**, 6**(15).
[22] R. Gellert, Natural fibre and fibre composite materials for insulation in buildings. In Materials for Energy Efficiency and Thermal Comfort in Buildings, 2010, p. 229, Woodhead Publishing.
[23] M. Palumbo, J. Avellaneda, A.M. Lacasta, Availability of crop by-products in Spain: New raw materials for natural thermal insulation. Resources, Conservation and Recycling, 2015, **99,** 1.
[24] Sodagar, B., Rai, D., Jones, B., Wihan, J., & Fieldson, R. (2011). The carbon-reduction potential of straw-bale housing. Building Research & Information, 2011, **39(1),** 51.
[25] M. Martiskainen, P. Kivimaa, Creating innovative zero carbon homes in the United Kingdom —Intermediaries and champions in building projects. Environmental Innovation and Societal Transitions, 2018, **26**, 15.
[26] D.L. Edmondson, K.S. Rogge, F. Kern, Zero carbon homes in the UK? Analysing the co-evolution of policy mix and socio-technical system. Environmental Innovation and Societal Transitions, 2020, **35**, 135.
[27] M. Pruteanu, Investigations regarding the thermal conductivity of straw. Buletinul Institutului Politehnic din Iasi. Sectia Constructii, Arhitectura, 2010**, 56(3),** 9
[28] J. Vėjelienė, A. Gailius, S. Vėjelis, S. Vaitkus, G. Balčiūnas, Development of thermal insulation from local agricultural waste. Proceedings of the 8th Environmental Engineering, Vilnius, Lithuania, 2011.
[29]. xxx, SR EN 12667:2002 Thermal performance of building materials and products. Determination of thermal resistance by means of guarded hot plate and heat flow meter methods. Products of high and medium thermal resistance
[30] xxx, EAD 040138-01-1201:2018 In-situ formed loose fill thermal and/or acoustic insulation products made of vegetable fibres
[31]. C. Petcu, D. Constantinescu, H. Petran, Experimental validation of the buildings energy performance (BEP) assessment methods with reference to occupied spaces heating, Rev. Construcții, 2010, **1**, 72
[32] D. Constantinescu, S. Cheval, G. Caracaş, A. Dumitrescu, Effective monitoring and warning of Urban Heat Island effect on the indoor thermal risk in Bucharest (Romania). Energy and Buildings, 2016, **127**, 452.
[33] D. Constantinescu, M. Constantinescu, C. Marin-Perianu, H. Petran, C. Petcu, A.G. Caracaş, E.M. Anghel, Principles and method of determining the thermal diffusivity of homogeneous and isotropic materials. Rev. Roum. Chim, 2011, **56(10-11),** 987
[34] xxx, Unitherm 6000, Guarded hot plate thermal conductivity instrument – User's Manual, v.2., 1999
[35] xxx, Lambda-Meßtechnik, Instruction Manual for the Thermal Conductivity Test Tool λ-Meter EP500e, 2012, Lambda-Meßtechnik GmbH Dresden
[36] xxx Portable System for Measurement of Heat Transfer Properties of Materials – User's Guide v. 1.47, 2011, Applied Precision Ltd. Stavitelska 1, 83104 Bratislava, Slovakia
[37] I.M. Miličić, R. Folić, A. Prokić, A. Čeh, Model for the analysis of thermal conductivity of composite material of natural origin. Thermal Science, 2019, **23(6A),** 3513.
[38] D. Jones, C. Brischke, Performance of bio-based building materials. Chapter 5.6 Thermal Performance. Woodhead Publishing, 2017.
[39] C. Petcu, H.A. Petran, V. Vasile, M.C. Toderasc, Materials from renewable sources as thermal insulation for nearly zero energy buildings (nZEB). In Conference on Sustainable Energy, 2017, p.159.
[40] J. Carfrae, The moisture performance of straw bale construction in a temperate maritime climate [Doctoral dissertation, University of Plymouth]. University of Plymouth Research Theses, 2011
[41] L. Conti, M. Barbari, M. Monti, Steady-state thermal properties of rectangular straw-bales (RSB) for building. Buildings, 2016, **6(4),** 44.
[42] S. Goodhew, R. Griffiths, Sustainable earth walls to meet the building regulations. Energy and Buildings, 2005, **37(5),** 451
[43] B. Krick, A Passive House Plus building made of bales of straw. Proceedings of the 20th International Passive House Conference, 2016, Darmstadt, Germania
[44] S. Kreutzer, Circuitus – What goes around comes around. Proceedings of the 20th International Passive House Conference, Darmstadt, Germania, 2016
[45] K. Wall, P. Walker, C. Gross, C. White, T. Mander, Development and testing of a prototype straw bale house. Proceedings of the Institution of Civil Engineers-Construction Materials, 2012, **165(6),** 377.
[46] Ghita, A. M., Asanache, H., Influence of the building materials thermal diffusivity over the behaviour of single-layer thick plates to a thermal excitation of impulse-type. Romanian Journal of Materials, 2015, **45(3)**, 240.
[47] xxx, C107/3-2005 Regulation regarding the thermotechnical calculation of construction elements of the buildings.
[48] xxx, SR EN ISO 10456:2007 Building materials and products. Hygrothermal properties. Tabulated design values and procedures for determining declared and design thermal values.

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