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INFLUENCE OF MOISTURE CONTENT OF MHM SOLID WOOD WALL CONSTRUCTION MATERIALS ON THERMAL CONDUCTIVITY

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ABSTRACT

The moisture content of materials in building structures is a factor that affects the amount of heat losses through the building envelope. In the context of the current demands for increased thermal protection, the moisture content of materials becomes an important indicator of thermal and technical properties. The paper is devoted to the theoretical and experimental analyses of the moisture condition of the construction materials of panel exterior walls made from solid MHM (Massiv-Holz-Mauer) panels. The theoretical analyses of the moisture status of materials through the WUFI 2D simulation program were supplemented by experimental measurements of moisture in built-in structures. The measurements took place in a research building simulating the creation of residential climate conditions. The research quantified the influence of the operating moisture status of MHM and blown thermal insulations (wood fibres and disintegrated straw) on their thermal conductivity. The research results show that the moisture content of MHM panels influences their thermal conductivity in natural conditions. However, in the case of wood-fibre insulation, no significant influence of moisture status on the coefficient of thermal conductivity was demonstrated. The moisture content of disintegrated straw indicates that in natural conditions, it acquires 46% higher thermal conductivity values than the ones declared by the manufacturer.

Keywords: moisture status of materials; thermal conductivity; MHM solid-wood panels; wood-fibre insulation; straw insulation.

INTRODUCTION

The thermal, hygroscopic, and moisture properties of timber constructions within the current trends in building construction represent an important factor related to the amount of heat losses through transition and the overall operational consumption of energy for heating.

In addition to the type of timber structure, its design plays a significant role. The design is strongly affected by the load-bearing system and the type of construction depending on which structure of the building envelope and the material composition are chosen. The chosen materials affect the thermal and moisture properties of the structure. Due to the significant portion of wooden structural elements and various wood-based materials in timber structures, the assessment of energy efficiency and heat losses of timber structures depends on the thermal and hygroscopic properties of these materials.

The thermal conductivity of construction materials strongly depends on the moisture content and density of the given construction materials (Asdrubali *et al.*, 2016). The results of the research conducted by Wang *et al.* (2019) point to the influence of moisture on the thermal conductivity of construction materials. Research into the basic thermophysical properties of spruce wood and wood composites under normal conditions was carried out by Regináč and Babiak (1977), Krišťák *et al.* (2019) and Božiková *et al.* (2021). Hrčka (2010) conducted research dealing with thermal properties of beech wood depending on humidity and density. The influence of moisture content in standard conditions was investigated when the moisture content of materials was around 12%.

Natural wood-base insulation materials have interesting moisture properties because of their high moisture capacity. Geving and Holme (2012), Geving *et al.* (2015), and Bunkholt *et al.* (2021) investigated the moisture properties of wooden panel constructions with wood-fibre thermal insulations. The results from the research of Geving *et al.* (2015) show that wall compositions with wood-fibre insulation behave similarly to those using mineral wool concerning relative humidity values on the outside of the structure. Laboratory tests have shown that wood-fibre insulation has interesting physical properties related to moisture absorption and transport. According to the study by Volf *et al.* (2015), natural-based insulation materials absorb more atmospheric humidity into their structure than, for example, mineral wool, which is due to their more complex organic structure.

With the growing interest in sustainable buildings that can reduce energy consumption and environmental impacts, the variability of straw-based constructions and their moisture properties are increasingly being investigated. Concerns about using straw in structures are mainly caused by the susceptibility of straw to the development of rot after being incorporated into the structure. Research conducted by Robinson *et al.* (2017), Carfrae (2009), and Cascone *et al.* (2018) dealt with assessing the influence of atmospheric conditions on the resulting moisture content of straw bales. Using straw as an insulating material in the construction of building envelopes significantly impacts the overall operational energy consumption in addition to an indisputably lower environmental burden. According to research by Volf *et al.* (2015), the heat transfer coefficient of straw compared to other natural-based insulating materials is the highest. However, the volumetric heat capacity of natural insulations and mineral wool is higher by 11% and 78%, respectively.

Based on the research, the values on the thermal conductivity of straw show a wider range than those of mineral insulations. This variability is due to the structure, type of straw insulation, moisture content, density, size, and air voids within the insulation and fibre orientation (Cascone *et al.* 2019).

Research conducted by Platt *et al.* (2022) points to different values of thermal conductivity of straw insulation also depending on the regulated orientation of the stalks – parallel and perpendicular to the heat flow. The use of straw processed by new production processes (chopping, drying, sorting, and cleaning) and a new method of its application in buildings – blowing, represents an area that has not been explored in practice so far from the point of view of its thermal and moisture behaviour in natural conditions.

The aim of the paper is to determine the effect of the moisture content of built-in construction materials of panel walls based on wood – solid MHM panels and blown thermal insulations (wood fibres STEICO zell and disintegrated straw TEPORE) on their thermal conductivity coefficient. The research was conducted by comparing the simulation in the WUFI 2D program and experimental measurements of the moisture status.

MATERIALS AND METHODS

A representative structural composition of an exterior panel wall made of wooden panels was designed to investigate thermal and moisture properties. The load-bearing structure consists of solid wood nail-laminated MHM panels. The thermal insulation envelope comprises lightweight ladder beams (LLB) (Fig. 1), which hold the insulation material and external siding. MHM panels are similar to CLT panels. In these cross-layered solid-wood parts, aluminium nails ensure the connection of the individual layers without using glue. The investigated structural compositions contain nature-based blown insulation materials that are not yet standard for this type of supporting system. To investigate moisture properties, two variants of structure composition with two types of thermal insulations were created: wood fibres STEICO zell (Fig. 2a) and disintegrated straw TEPORE (Fig. 2b).

Fig. 1 Solid-wood panels – MHM and lightweight ladder beams in the exterior wall of the research structure.

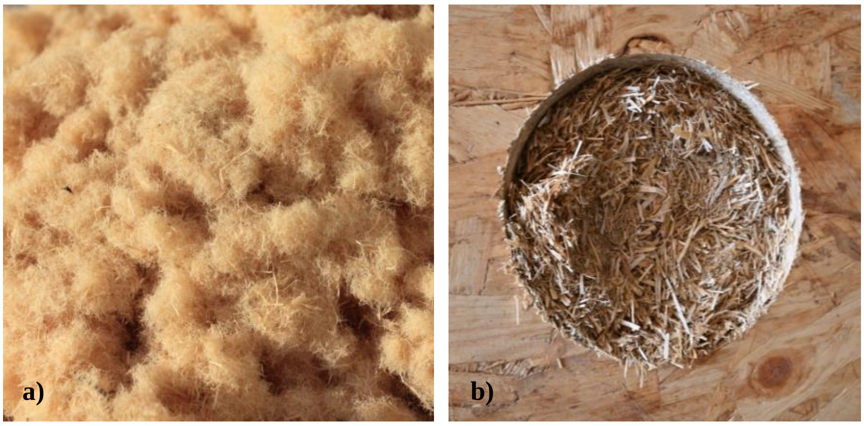

Fig. 2 Wood fibres STEICO zell (a) and disintegrated straw stalks TEPORE (b).

The basic physical parameters of the investigated insulation materials which we used as a basis for the research are listed in Tab. 1.

Tab. 1 Physical parameters of investigated insulating materials – wood fibres and disintegrated straw

S.n.	Material	Density ρ_d [kg/m^3]	Coefficient of thermal conductivity λ [W/(m.K)]		Thermal capacity c [J/(kg·K)]	Diffusion resistance coefficient μ [1]
			proposal	declared		
1.	Blown wood-fibre insulation STEICO zell	38 – 45 (1)	0.040	0.038	2 100	1 - 2
2.	Blown disintegrated straw TEPORE	105 – 140 (1)	0.057	0.055	2 000	1.3
Comments: (1) Application density of insulating material – application by blowing. All technical parameters listed in the table are available in the technical data sheets of the manufacturers.						

The composition of the installed fragments of the structures is shown in Fig. 3 (a description of the composition is below Fig. 3).

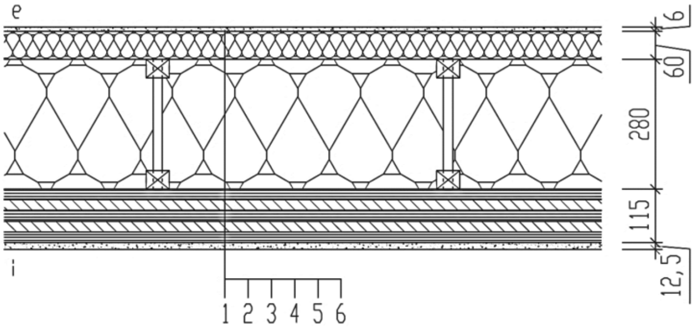

Fig. 3 Composition of exterior wall constructions from MHM and lightweight ladder beams.

Composition of the exterior wall constructions *MHM_VN*: (according to Fig. 3)

1.	*Plasterboard – GKF*	*12.5 mm*
2.	*Solid-wood nailed structural elements – MHM (5 layers)*	*115 mm*
3.	*Lightweight ladder beam 6283 + natural-based blown thermal insulation (wood-fibre insulation STEICO zell or disintegrated straw TEPORE)*	*280 mm*
4.	*Wood-fibre facade thermal insulation*	*60 mm*
5.	*Adhesive mortar for wood-fibre insulation + reinforcing mesh*	*3 mm*
6.	*Mineral facade plaster*	*3 mm*

The assessed structural compositions were a direct part of the exterior walls on the south side of the research structure, simulating the standard climate of residential structures (Fig. 4).

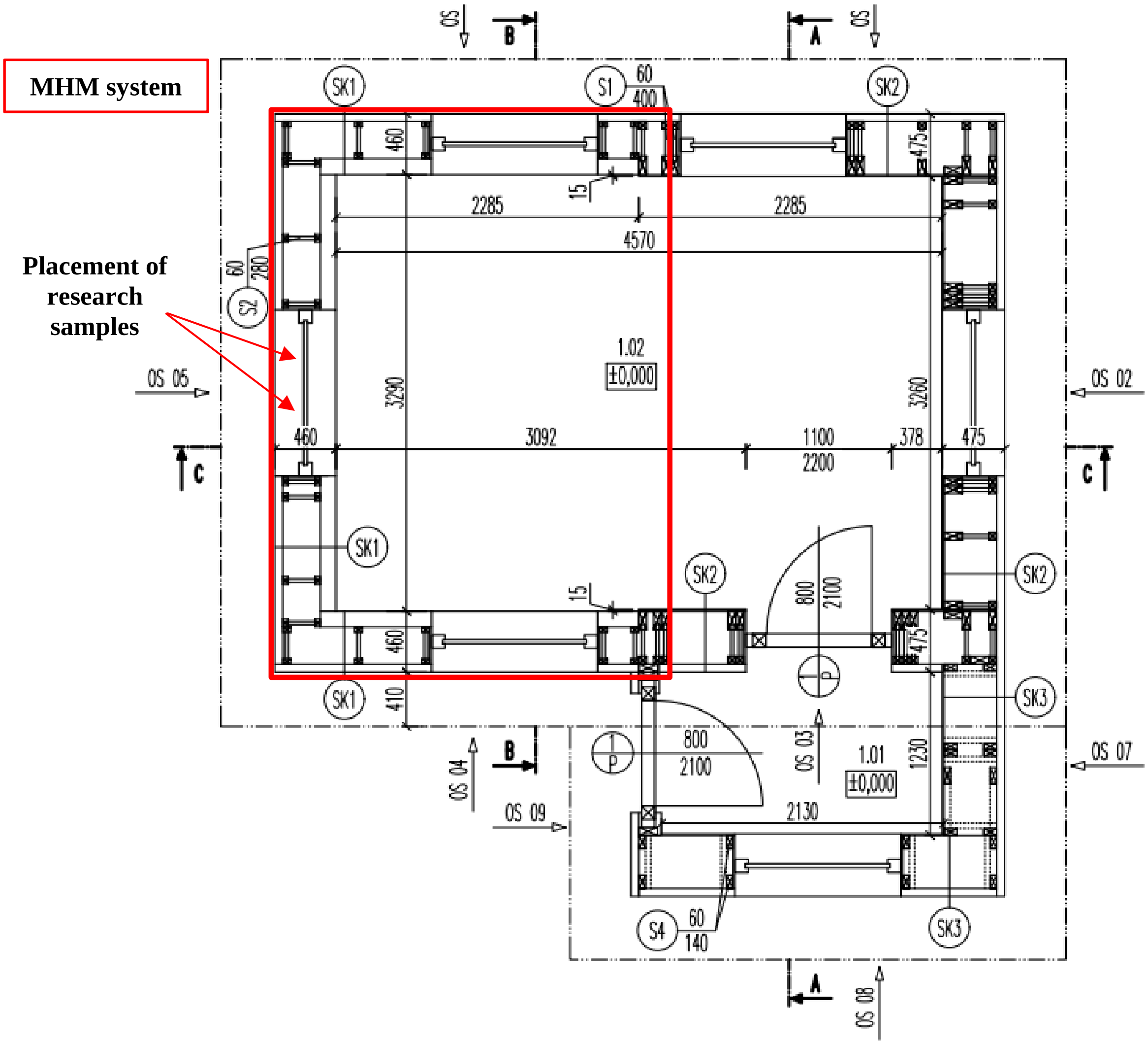

Fig. 4 Prototype research structure use of different load-bearing systems based on wood.

Control holes were made in the built-in constructions (one control hole for each type of structure), which were used for the installation of sensors and insertion of material samples for determining the moisture content. Polyvinylchloride (PVC) pipes with a diameter of 120 mm and length of 280 mm were embedded in the places of control holes in the area of thermal insulation. These were used to store net bags with blown thermal insulation materials and separate them from the surrounding insulation. The holes were also used to install sensors for measuring temperature and relative humidity developments. Thermal insulation was divided into three equally thick parts (93 mm thick), creating three separate samples for further research of the thermal insulation moisture properties.

Sensors and measuring technology

To determine temperature development on the structure's outer and inner surfaces, separate thermocouple sensors θ_x were placed in the fragments (NiCr-Ni thermocouple sensors with range of -10 to +105 °C from AHLBORN company).

Digital sensors from AHLBORN company $\theta_{b,\ x}$ ($T_{b,\ x}$) were used to measure temperature, relative humidity, and air pressures. An exterior digital sensor from AHLBORN company with a protective cover was used to measure exterior climate parameters.

The measuring sensors were built into the constructions of the southern exterior wall of the research structure through control holes (Fig. 5). Measurements were recorded at hourly intervals throughout the research. The data were recorded using the ALMEMO measuring centre.

Fig. 5 Installed sensors in the construction of MHM exterior panel wall.

Temperatures and relative humidity of the air outdoors, indoors, and inside the fragments of walls were measured by the mentioned measuring devices.

Disposition of sensors

Fig. 6 shows a cross-section within fragments of the investigated structures with a schematic representation of the location of the sensors in the individual structural layers.

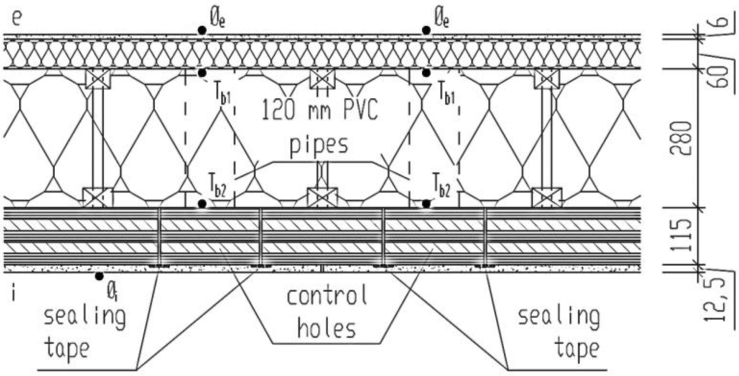

Fig. 6 Built-in sensors (θ_x, $T_{b,x}$) for measuring temperature and relative humidity in the structures.

Indoor environment parameters were maintained in the research structure by the air temperature adjustment unit and a separate humidification system during the research.

The values of the moisture state of the investigated construction materials in the fragments were determined by the gravimetric method which is precisely described in STN EN 322. The samples of the construction materials were weighed on laboratory scales (RADWAG PS 3500.R2.M) at weekly intervals during the entire period. The mass measurements were made with an accuracy of 0.01 g. The drying process of samples to an oven-dry state was performed in the laboratory kiln at 103 ± 2 °C. The samples were weighed until reaching the steady state, when a mass difference lower than 0.1% was reached after three successive weights in 24 h, the equilibrium was considered to be reached.

The influence of the actual moisture status of construction materials on their thermal conductivity was assessed by an analysis with the WUFI 2D program. The calculation program has an extensive library of materials within which the dependence of thermal conductivity λ on the moisture content of materials is assigned. The calculation program also considers the sorption properties of materials and the possible redistribution of moisture into their structure. The influence of the actual moisture status of materials on the change in the coefficient of thermal conductivity was assessed in pursuance of the data from experimental measurements.

RESULTS AND DISCUSSION

Fig. 7 shows the relative humidity and air temperature trends in the research structure during the entire period of the measurements. The values were measured by a digital sensor $T_{b,x}$ placed in the interior of research structure. The values of relative humidity fluctuated in the range from 22.8% to 61.10% (average value was 36.9%). The average indoor air temperature during the measured period was 20.91°C.

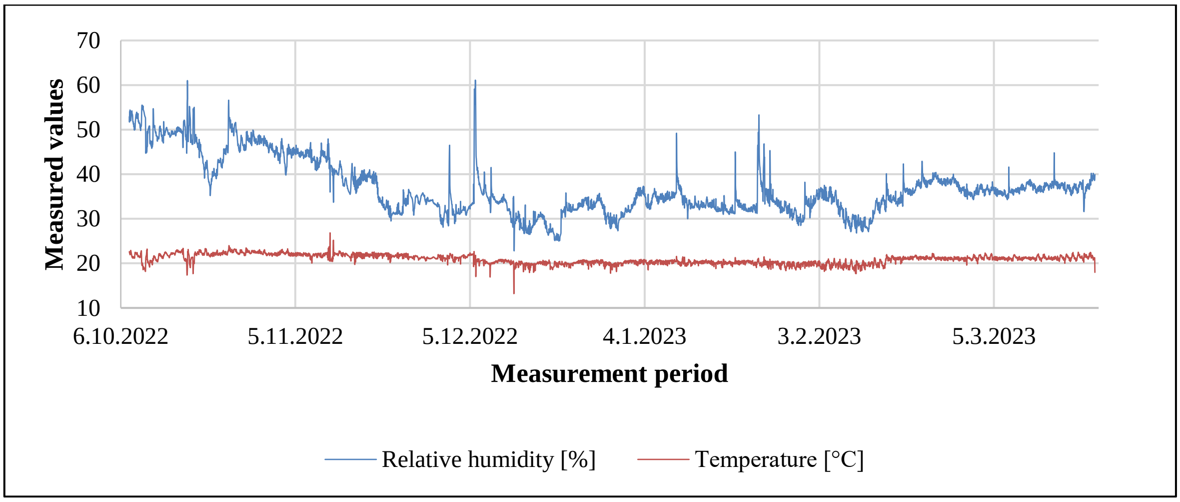

Fig. 7 Interior temperature and relative air humidity in the research structure during the whole period of measurements.

The development of temperature and relative humidity in the exterior during the research period is shown in Fig. 8. The values were measured by digital sensor $T_{b,x}$ designed for exterior use.

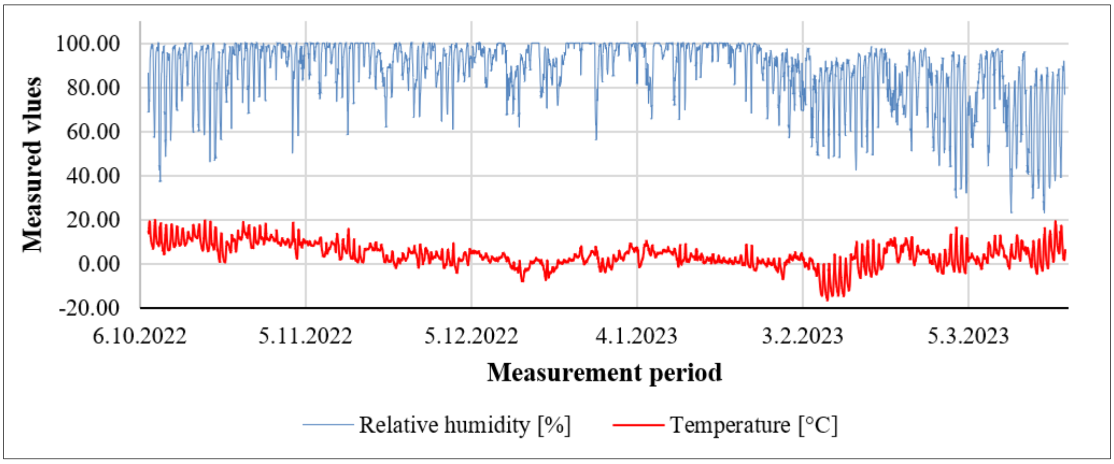

Fig. 8 Exterior temperature and relative air humidity during the whole period of measurements.

According to the measured data (Fig. 8), the average outdoor relative humidity was at the level of 87.16%, which reached its maximum of 100% several times in the period from December 2022 to January 2023. The lowest measured outdoor temperature was -16.73°C (2/7/2023 at 8:00 a.m.).

Fig. 9 shows the development of the moisture content of solid-wood MHM panels in the research fragments. The moisture content of the MHM samples was determined by the gravimetric method.

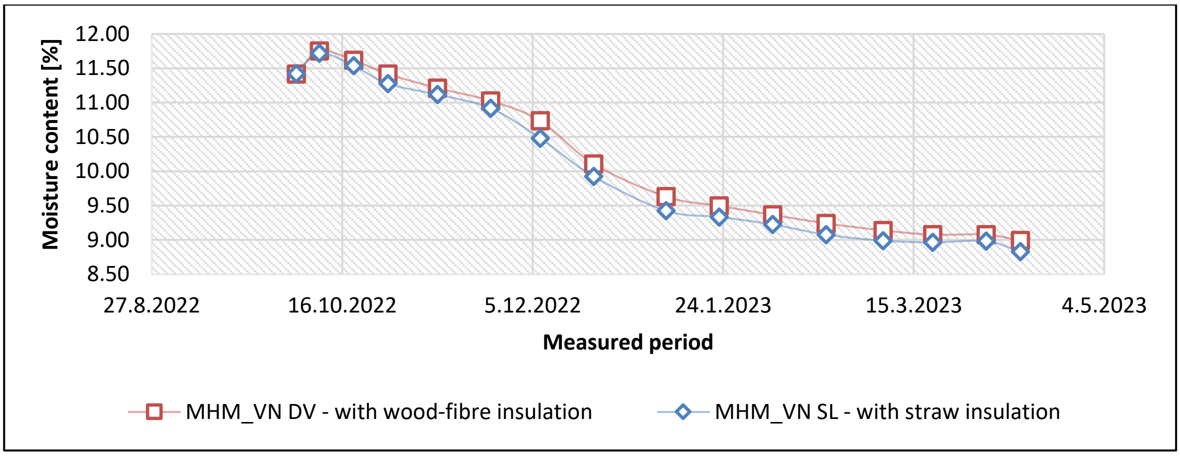

Fig. 9 Moisture content of MHM panels in research fragments.

Fig. 10 represents the dependence of thermal conductivity (λ) on the moisture content of soft coniferous structural wood referring to bound water according to the available data from the WUFI 2D program. The graph does not include free water in the material. Under standard conditions, the moisture content of the built-in MHM samples in the structure does not exceed 12% which excludes any presence of free water during its use.

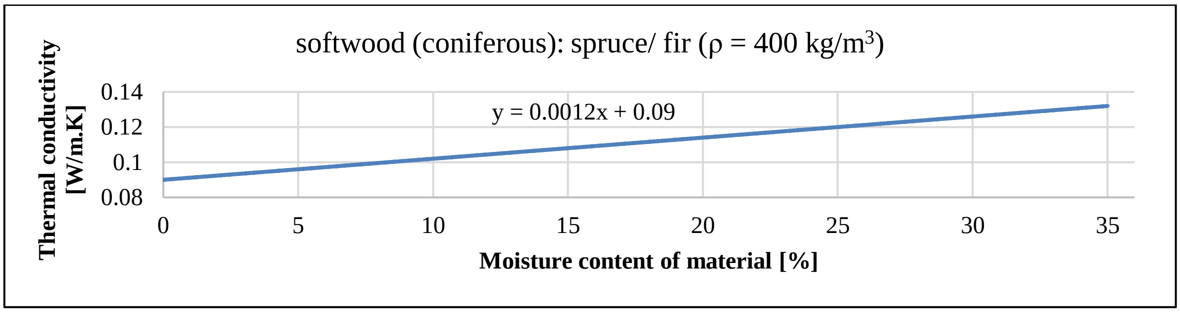

Fig. 10 Dependence of thermal conductivity (*λ*) on moisture content (*w*) of soft coniferous wood – spruce/ fir (WUFI 2D).

The data in Fig. 9 show that the moisture content of solid-wood MHM samples ranged from 8.81% to 11.93%. The results of WUFI 2D program show that the values of relative humidity ranged from 9.50-10.60%. The coefficient of thermal conductivity for calculations of thermal properties was considered at the level of $\lambda = 0.13$ W/(m.K) according to STN EN ISO 10456. Based on the dependence of thermal conductivity on the moisture content of soft coniferous wood (Fig. 10), the moisture content for this value is 33.25%. the measured data show that the moisture content of the MHM samples was at a significantly lower level, and the calculated value of the thermal conductivity coefficient is overestimated in favour of the safety of its use. The coefficient of thermal conductivity could be considered at the level of $\lambda = 0.105$ W/(m.K), which corresponds to a moisture content of material approximately 12% below which the measured humidity values ranged. The heat flow through the MHM samples in the exterior wall was in the perpendicular direction (predominantly in the tangential direction of plates).

Theoretical calculations are based on the standards (STN 73 0540 and STN EN ISO 10456) for the soft coniferous wood (spruce/fir), which state a higher coefficient of thermal conductivity lambda in favour of safety for theoretical calculations of thermal properties. According to the measured data and a theoretical comparison, it is clear that the thermal conductivity of MHM panels in perpendicular direction ranged from $\lambda = 0.102$-0.105 W/(m.K). This corresponds to the value declared by the manufacturer for $\lambda = 0.11$ W/(m.K). These data indicate that the theoretical design value of thermal conductivity for calculations of thermal-technical properties of walls according to STN EN ISO 10456 is significantly in favour of safety, and it could be reduced by an average of 20.4% assuming an optimal moisture condition, which in the construction occurs without design and structural defects. The experimental measurements made by Kotoulek *et al.* (2018) show that the thermal conductivity of soft coniferous wood samples perpendicular to the fibres is in the range of $\lambda = 0.103$ - 0.108 W/(m.K) (depending on the direction). Tab. 2 shows the results from the research of Kotoulek *et al*. (2018).

Tab. 2 Thermal conductivity of soft coniferous wood at a laboratory temperature of 20 °C (adapted from Kotoulek *et al*. 2018)

Samples/ direction of fibres	Coefficient of thermal conductivity – λ [W/(m.K)]. Arithmetic mean.	Relative deviation [%]
Radial	0.108	± 2.12
Tangential	0.103	± 1.07
Longitudinal	0.275	± 0.84

The results of the research conducted by Flity *et al.* (2024) state that the thermal conductivity of spruce perpendicular to the fibres at equilibrium moisture content and temperature of 20 °C ranges from λ = 0.111-0.114 ± 0.06 W/(m.K). The authors demonstrated the dependence of thermal conductivity on the density of material which means that thermal conductivity is also affected by the occurrence of defects in wood – knots, cracks.

As part of further research, the thermal conductivity could be adjusted based on the density of the material in addition to the moisture.

Fig. 11 shows the moisture course of three parts of blown wood-fibre thermal insulation (STEICO zell). The moisture content of the STEICO zell samples was determined by the gravimetric method. Fig. 12 represents the dependence of thermal conductivity (λ) on moisture content for STEICO zell taken from the WUFI 2D program.

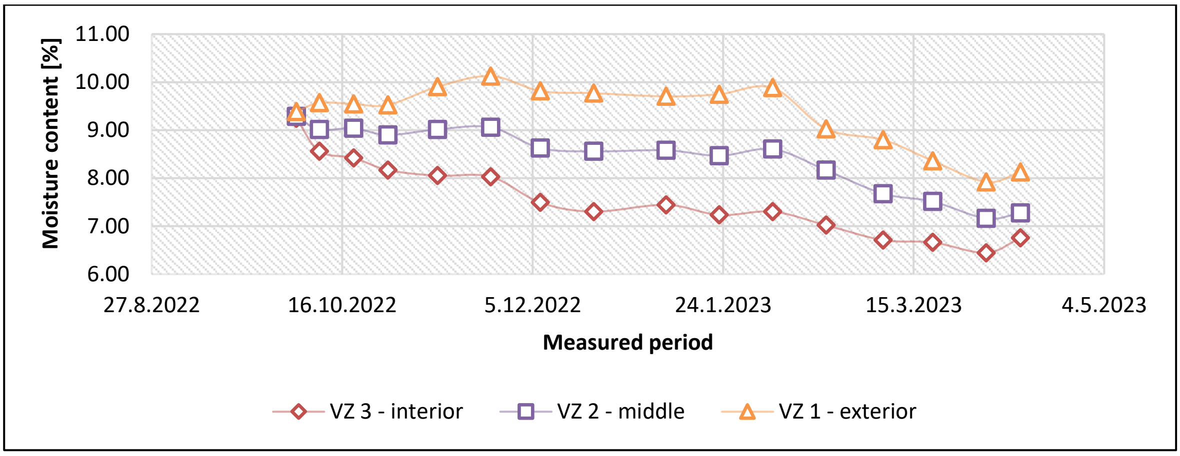

Fig. 11 The course of moisture content of three parts of blown thermal insulation STEICO zell (*MHM_VN DV*).

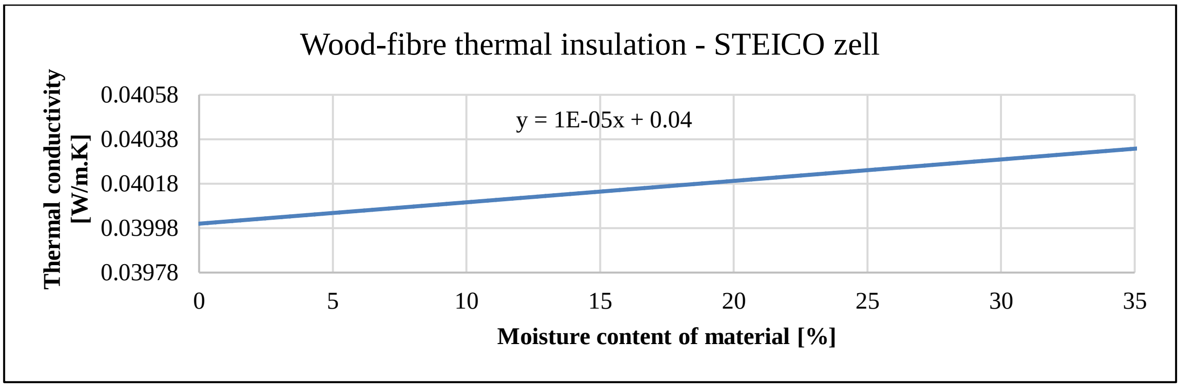

Fig. 12 Dependence of thermal conductivity (λ) on moisture content (w) of STEICO zell (WUFI 2D).

The moisture content of STEICO zell ranged from 6.45% to 10.13% (Fig. 11). The insulation acquires the highest moisture content in the layers on the exterior side and the lowest on the interior side. The expected moisture content of the STEICO zell according to the WUFI 2D program was in the range: 4.40-6.00% on the interior side; 4.30-5.95% in the middle section; and 4.20-5.98% on the exterior side of the structure. The differences between the exterior and interior sides and theoretical simulation and real values are caused by the convection of moist air from the exterior into the structure.

The results from the experimental measurements of the moisture content of STEICO zell (Fig.11) show that the moisture content in actual conditions did not exceed a level that would affect the design thermal conductivity of the material (declared by the manufacturer).

According to the data in Fig. 12, the coefficient of thermal conductivity, depending on the moisture content, almost does not change. The influence of moisture content is minimal in this range. According to the available data, the thermal conductivity λ would change by 0.001 W/(m.K) up to 103% moisture content. This value represents an amount of water of approximately 41.2 kg/m^3 of material at an average density of 40 kg/m^3 blown insulation. In actual conditions, a moisture content that would significantly affect the thermal conductivity of the STEICO zell was not reached. In the study of Gullbrekkena *et al*. (2019), the coefficient of thermal conductivity of wood-fibre insulation deteriorated in the complete moisture saturation by only 0.001 W/(m.K) compared to the original value. The research demonstrated that the thermal conductivity is not affected by moisture content on the hygroscopic area of this material.

The course of the moisture content of TEPORE disintegrated straw insulation is illustrated in Fig. 13. The moisture content of the disintegrated straw TEPORE samples was determined by the gravimetric method. Fig. 14 represents the dependence of thermal conductivity (λ) on moisture content for straw thermal insulation according to the WUFI 2D program.

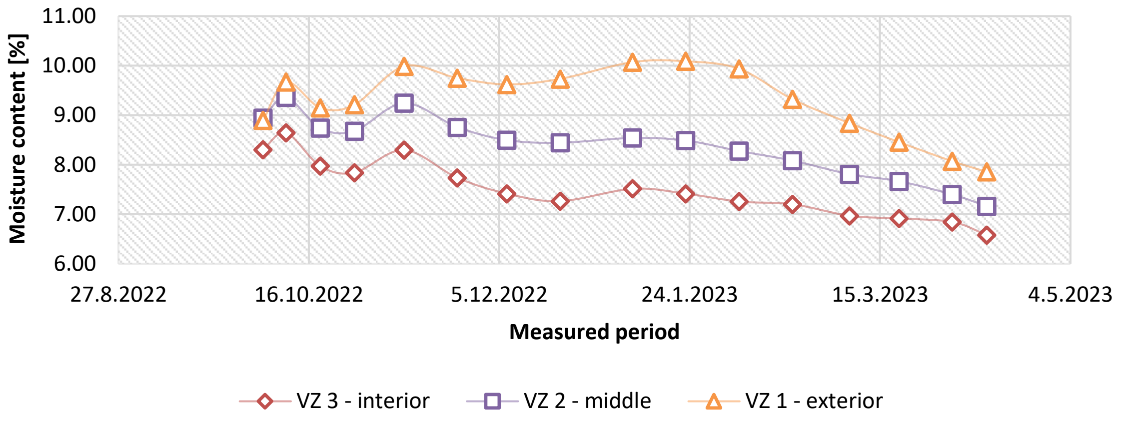

Fig. 13 The course of moisture content of three parts of disintegrated straw thermal insulation TEPORE (*MHM_VN SL*).

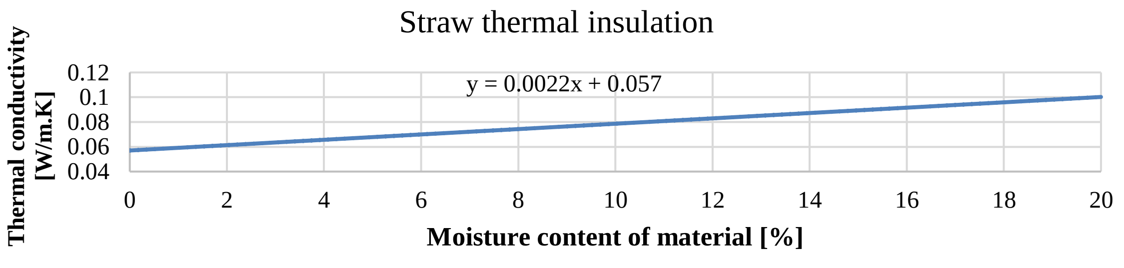

Fig. 14 Dependence of thermal conductivity (λ) on moisture content (w) of straw thermal insulation (WUFI 2D).

According to the data in Fig. 13, the moisture content of straw thermal insulation ranges from 6.58% to 10.09%. The moisture content is higher on the exterior side of the thermal insulation layer and decreases towards the interior. The expected moisture content of the straw thermal insulation TEPORE according to the theoretical simulation in the WUFI 2D program was in the range: 4.85-6.05% on the interior side; 4.80-6.05 % in the middle section; and 4.70-6.00% on the exterior side of the structure. The differences between theoretical simulation and measured values are caused by the convection of moist air from the exterior into the structure in real conditions.

The coefficient of thermal conductivity of the material changes significantly even at lower moisture values. According to the measured data (Fig. 14), the thermal conductivity coefficient is λ = 0.0698 – 0.0828 W/(m.K) at 6-12% moisture content. These facts indicate that the calculated value of the coefficient of thermal conductivity λ = 0.055 W/(m.K) (mentioned by the manufacturer's technical datasheet) is not correct and should be increased to the level of at least λ = 0.083 W/(m.K). This coefficient would correspond to the highest measured moisture content in the straw thermal insulation layer. The coefficient of thermal conductivity declared by a manufacturer should be increased by at least 46% when calculating the influence of moisture content up to 12%.

The available data from research on the thermal conductivity of straw mention a broader range than, for example, mineral thermal insulation. The variability in properties is caused by the structure and type of straw insulation, moisture content, density, size, and the number of air voids within the insulation material and fibre orientation (Cascone *et al.*, 2019). Therefore, according to Cascone *et al*. (2019), in the thermal and technical assessment of structures using straw insulations, it is difficult to identify suitable values that would subsequently be used for simulation programs in the calculation of the thermal and moisture behaviour of structures. In the study, the authors demonstrated that the thermal conductivity of dry straw or straw bales is at the level of λ = 0.0573 W/(m.K) in perpendicular direction. According to their study, for the calculation of thermal technical properties, the value should be increased by at least 20% to λ = 0.07 W/(m.K). In the research of Teslík (2016), the average (declared) value of thermal conductivity of disintegrated straw was determined by experimental tests at λ = 0.053 W/(m.K) at density of 90-110 kg/m^3. Teslík (2016), however, did not monitor the influence of moisture content on thermal conductivity. Tab. 3 presents data about the thermal conductivity and density of straw in different forms.

Tab. 3 Thermal conductivity λ and density ρ of straw bales by different authors (adapted from Cascone *et al*. 2019).

Authors	Year	Coefficient of thermal conductivity – λ [W/(m.K)]	Density – ρ [kg/m^3]
Goodhew and Griffiths	2005	0.07 – 0.09	60 - 90
Shea *et al*.	2012	0.059	63
		0.062	76.3
		0.062	87.4
		0.064	107
		0.064	114
		0.065	123
Zhang *et al*.	2017	0.074	-
Gallegos-Ortega *et al*.	2017	0.094	115

Based on the data from Tab. 3, we can state that the coefficient of thermal conductivity of straw, whether in the form of compact straw bales or disintegrated particles, acquires a wide range of values due to various factors as we have already mentioned. According to the results from our research, we can say the coefficient of thermal conductivity of disintegrated straw λ = 0.0698-0.0828 W/(m.K) at the material moisture 6-12% is within the range and corresponds with the results of studies by mentioned authors in Tab. 3.

CONCLUSION

The paper deals with theoretical and experimental research focusing on the moisture status of construction materials of exterior panel walls from MHM solid-wood and lightweight ladder beams using natural-blown thermal insulations. The research quantified the influence of standard moisture content on the thermal conductivity of the supporting structure and the main insulating materials in operating conditions. This effect was insignificant in the case of wood-fibre insulation STEICO zell. However, even the lower operational moisture content of disintegrated straw insulation TEPORE inside the structure significantly affects its thermal conductivity.

Provided the envelope structures are correctly implemented, the moisture level of blown wood-fibre insulation STEICO zell does not significantly affect its thermal conductivity. The material would have to reach up to 103% moisture content, should the coefficient of thermal conductivity change by 0.001 W/(m.K).

The results from the research of disintegrated straw insulation TEPORE showed that the manufacturer-declared value of the coefficient of thermal conductivity λ was significantly influenced by the moisture range w = 6-12%. According to the results, the coefficient of thermal conductivity should be increased by at least 46% (from 0.057 to 0.083 W/(m.K)) for this type of insulation. An increase in the coefficient of thermal conductivity degrades the heat transfer and increases the heat loss through building envelope. The results should be considered when calculating the thermal properties of peripheral constructions of buildings (such as exterior walls) using an increased coefficient of thermal conductivity λ.

The research on the moisture status of wood-based materials has shown that their usual value of thermal conductivity according to STN EN ISO 10456 and STN 73 0540 is highly overestimated. In real atmospheric conditions within the exterior walls, the moisture status of wood-based materials (MHM) reached lower values than the data in STN EN ISO 10456 and STN 73 0540, by 20.4% and 57.5%, respectively. The value of the coefficient of thermal conductivity for MHM panels, which was determined, also corresponds to the value declared by the manufacturer (λ = 0.11 W/(m.K)).

The comparison of theoretical and experimental results of the moisture content in thermal insulations STEICO zell and disintegrated straw TEPORE in the WUFI 2D program showed significant differences between the theoretical simulations and real results from the measurements of the built-in materials in the structure.

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