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Laboratory tests on properties of innovative natural thermal insulation material

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ABSTRACT

Nowadays, there is an increasing demand on environmentally friendly materials, so the environmentally conscious architecture and the use of environmentally friendly materials have also become preferred. It is becoming increasingly important to turn from artificial materials to products made from renewable raw materials. The straw quilt, which is considered to be a new, innovative product on the Hungarian construction market, can provide an alternative for this need. The aim of this research was to investigate the material properties and possible uses of straw quilt thermal insulation. Laboratory tests were performed before the product was placed on the market. The results have shown that it has several advantageous properties that can make it competitive in the market of thermal insulation materials.

KEYWORDS

thermal insulation, straw, innovation, straw quilt, natural, energy-conscious architecture, environmentally friendly

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1. INTRODUCTION

In the 21st century humanity has faced serious global problems (e.g., climate change) caused by the unprecedented environmental pollution generated by the increasing energy consumption. Due to the excessive consumption of non-renewable fossil fuels and the resulting drastic increase of greenhouse gas emission have led to the preference for technologies based on renewable resources. Nowadays it has become clear that there is no other way to sustain the life on our planet [1].

In recent decades, energy- and environmental-conscious thinking has received considerable attention in all fields of life, including buildings and construction sector, which is responsible for 36% of the European Union's total energy consumption and 37% of its greenhouse gas emission. Therefore, it can be concluded that there is a huge potential for energy savings in buildings and construction sector [2, 3].

The increasingly stringent requirements about the energetic performance of buildings, the spread of passive and nearly zero-energy buildings, the use of renewable resources, the selective collection and utilization of construction and demolition wastes and the increasing number of energy saving renovations all prove that there are many efforts in architecture [4]. Thermal insulation of buildings has become a significant point of architectural design, as it acts a huge role in reducing the energy used for heating, which accounts for 70% of the energy consumption of buildings [5].

In the context of sustainability, the life-cycle assessment of buildings has become a priority, which includes the energy required by production and installation of building materials and building structures, as well as what happens if they become unnecessary or waste (e.g., possibility of reuse, recycling or disposal, energy consumption of waste management) [6–8].

Currently, the market for thermal insulation materials is dominated with a share of over 90% by artificial products; their manufacturing process requires large amounts of non-renewable energy sources [9]. However, in the spirit of environmentally conscious architecture, it is worth considering the use of renewable, natural materials as a possible alternative [10, 11]. Unfortunately, trends show that designers, investors, and contractors prefer the use of conventional artificial insulation materials, the most alternatives are missing from the public consciousness, their prices are often relatively high (e.g., hemp, sheep wool) and they are surrounded by a high degree of distrust due to a lack of reliable literature, standards, and other technical regulations [12].

2. THE STRAW QUILT

The thermal insulation properties of natural materials were recognized very early. The first materials specifically manufactured for thermal insulation were appeared in the second half of the 19th century (dried seagrass, bagasse, hemp, flax, cork, wood wool, fiberboard). The use of straw in construction was also common, because in the early history there were building structures which were made by the application of straw (e.g., thatched roofs, addition of straw chippings to the adobe) [13].

Although the first straw-bale house in Hungary was built only in the 2000s, the straw-bale construction is also a historical use of straw in construction, as it was already developed in the United States in the 1880s [14, 15].

In parallel with the straw-bale construction, some attempts to produce building boards from pressed straw were reported in 19th century, like the patent of B. Nicholl in 1867 and the patent of Judd M. Cobb in 1871 [6]. The first pressed straw board, which could also be used for construction, was patented in 1923 by the French-Russian Sergei Nikolayevich Tchayeff [7]. The raw material was straw chips, which was compressed in a hydraulic press and bonded together with galvanized steel wires [16, 17]. The product was previously available in Hungary under the trademark Solomit, and it has been produced in Australia under this name since 1937 to this day [13]. The first thermal insulation board made of pressed straw was developed in Sweden by Theodor Wright Dieden in 1935 [16]. The product was marketed by Torsten Johannes Mosesson in 1945 under the trademark ‘Stramit’ and it was spread as an in-fill insulation of wood-frame structures [16]. Since the 1980s in the United States and Canada (and since 2009 in China wheat and rice straw-based building boards) Oriented Structural Straw Board (OSSB) has been produced using high-pressure heat compression [18].

The straw quilt in Hungary has been produced by a manufacturing plant in Tinnye (Pest County) since November 2020 [19]. Its raw material is cereal straw, of which Hungarian farms harvest 60%, usually in the form of bales, and the rest of it is burned on the stubble or plowed back into the ground. Most of the harvested cereal straw (50–55%) is used for animal bedding and manure, a smaller amount (25–30%) is used for mushroom compost or utilized as the raw material of cellulose production and the remaining 15–25% is burned as biomass [19] or used for biogas production [20]. Its advantage is that it is a cheap and renewable raw material (agricultural by-product), it can be usually obtained nearby (low transport costs), and it is available in large quantities, because 7.5 million tons of cereal straw is produced in Hungary per year [21].

The production size of straw blankets made in Hungary is 50 × 100 cm, which is mounted with white linen or brown jute fabric, which helps to distinguish it, as the production density of quilts with white linen fabric is 100 kg m^{-3}, while that of jute fabrics is 90 kg m^{-3}. They are made using a special machine capable of automatically cutting, compacting, and sewing the straw. The straw is loaded into the machine through a feeding tray. The machine cuts the straw to size and then sews them together with the mounting using a high-performance sewing machine, which compresses it at the same time.

The straw quilt can be plastered well, mostly using lime or adobe plaster (cement is avoided), with traditional manual method and traditional plastering tools. The plaster increases the mechanical strength, improves the stiffness and the fire and moisture resistance; moreover, protects the straw from decomposition. Its advantage can be found in its environmental consciousness, as it contains a large amount of carbon dioxide bounded from the atmosphere, its production is not energy-intensive, and after becoming construction waste it is not classified as hazardous material (it decomposes easily when it returns to the nature) [22].

3. LABORATORY TESTS

The pre-commercial qualification tests of the straw quilt were performed in the Laboratory of Building Materials and Building Physics of Széchenyi István University, Győr, Hungary, to make its material properties comparable with other well-known thermal insulation materials and to determine the limits of its use and applicability. The required test specimens were provided by the producer, 21 samples of 20 × 20 cm, 3 samples of 15 × 30 cm, 6 samples of 30 × 30 cm and 5 samples of production size of 50 × 100 cm were prepared for the tests (Fig. 1).

3.1. Density

Density tests were made with the samples of 20 × 20 cm and 30 × 30 cm according to EN 1602:2013 standard [23], but due to the large standard deviation of measurements on smaller samples, only data measured on 30 × 30 cm samples were considered to be relevant. The results showed that the average volume density of the linen mounted product was 103.45 kg m^{-3} (standard deviation: 2.24 kg m^{-3}), while that of the jute mounted product was 86.52 kg m^{-3} (standard deviation: 1.78 kg m^{-3}).

3.2. Weight loss

The straw quilt does not contain bonding agent; it is only held together by the seams. Therefore, the straw may fall out of the product during the transportation, the on-site moving or as a reason of inappropriate on-site handling (e.g., throwing, dropping). This phenomenon was also observed during the

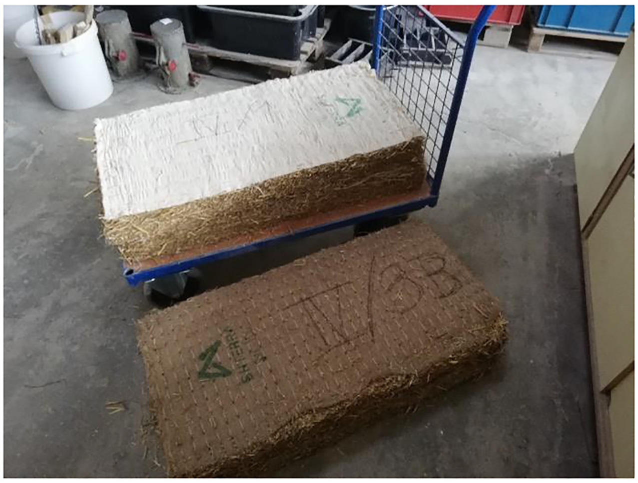

Fig. 1. Straw quilt specimens with 50 × 100 cm production sizes (*photo*: Rebeka Ábrahám-Horváth)

tests, especially in case non-production size specimens where the seams were damaged due to the cutting of the samples. This promoted to test how much weight loss occurs as the straw quilt is transported or suffers from improper on-site handling.

As no standard was available, the conditions were simulated in a unique way. To model road transport, the specimens were placed on a handcart, which was intentionally pulled in order to shake as much as possible during the traveling. Improper handling was simulated by dropping the specimens three time from a height of 1.5 m. Based on the results, it can be stated that straw quilts suffer a weight loss of 2.4% during road transport, while 4.6% weight loss due to improper handling (dropping, throwing).

3.3. Thermal conductivity

Tests according to EN 12667:2001 [24] were performed on specimens with dimensions of 30 × 30 cm using Taurus TCA 300 thermal conductivity measuring instrument. Samples were tested in transport condition, at an average natural moisture content of 8.01%, in an air-dry condition, and after the water absorption tests, even in wet condition. Based on the results, the thermal conductivity of straw quilt at an average temperature of 10 °C was 0.401 W mK^{-1} (standard deviation: 0.008 W mK^{-1}) in air dry condition, 0.0434 W mK^{-1} (standard deviation: 0.004 W mK^{-1}) with natural moisture content, and 0.0747 W mK^{-1} (standard deviation: 0.012 W mK^{-1}) in wet condition state. Based on the values measured in air-dry condition, it can be stated that the thermal insulation capacity of straw quilt is the same as that of conventional and well-known materials, like expanded polystyrene foam and rock wool.

3.4. Water absorption

Water absorption of thermal insulation materials can be tested with partial and full immersion. According to EN 1609:2013 standard [25] the duration of partial immersion test can be short-term (24 h) and long-term (28 days). As straw quilt is a natural material, there was no reason to run a 28-day test, so only short-term water absorption was determined.

Specimens of 20 × 20 cm were used for the measurements. After 2 days of conditioning under normal laboratory circumstances ($T = 23 \pm 2$ °C, $\varphi = 50 \pm 5\%$), they were placed in a water tank so that their lower surface was 10 ± 2 mm below the water level. Based on the results the short-term water absorption 1.312 kg m^{-2} (standard deviation: 0.157 kg m^{-2}), which is similar to the water absorption of rock wool, much lower than in case of most natural materials (e.g., hemp, sheep wool, cellulose), although it is higher than the water absorption of cork (0.5 kg m^{-2}).

The water absorption test with full immersion was performed according to EN 12087: 2013 standard [26]. It prescribes long-term (28 days) immersion; however, as straw quilt is a natural material, it was not well-founded to run the test for this long period of time. As a conclusion, the water absorption was determined after 1, 24 and 120 h (5 days), contrarily to the standard. During the test, the samples were placed in a container filled with water so that their upper surface was 50 ± 2 mm below the water level. The mass measurement results (Table 1) showed that samples with higher volume density (i.e., samples with linen mounting) had higher water absorption. It has also been shown that the water absorption of the material is extremely fast, especially in the first hour. Over the next 23 h, the increase in water absorption was 9.7% in case on samples with linen mounting and 9.8% in case of samples with jute mounting. These values increased with 8.1% and with 16.1% during the next 4 days.

In terms of water resistance, it can be stated, that after 24 h spent underwater a yellowish-brown discoloration of water was observable. After a week, a brown film also formed on the surface of the water, and the product began to emit an unpleasant smell and began to show the signs of rot. After another week, this membrane grew, the smell intensified, and strong shape losses and deformations of the sample were observed. This made it clear that the material is sensitive to long-term moisture effect, which must also be

Table 1. The evolution of the water absorption in time with full immersion

Time (hour)	Symbol	Dimension	Mounting	
			Linen	Jute
0	m_0	g	358.01	293.70
1	m_1	g	1253.47	954.98
	w_1	g	895.46	661.28
		%	250.12	225.15
24	m_{24}	g	1375.24	1048.69
	w_{24}	g	1017.23	754.99
		%	284.13	257.06
120	m_{120}	g	1486.71	1170.05
	w_{120}	g	1128.70	876.35
		%	315.27	298.38

considered during the installation. It should be avoided in places where it is permanently exposed to water, or it should be protected against moisture. As a result of water absorption, straw quilt also suffered dimensional changes. Increasing in volume was 4.20% in the first hour and by a further 4.03% after 24 h and a further 2.88% after 120 h.

3.5. Dimensional stability

There are two ways to determine the dimensional stability of thermal insulation products. According to EN 1603:2013 [27], the test is performed on samples of production size under normal laboratory conditions ($T = 23 \pm 2$ °C, $\varphi = 50 \pm 5$%). The results showed that the straw quilt had a length change of −0.02% (0.2 mm), a width change of −0.08% (0.4 mm) and a thickness change of −0.20% (0.2 mm). Its decrease in volume was 0.30% and its volume density decreased by 0.33% (weight change was considered).

EN 1604:2013 [28] is used to determine the dimensional stability under specified temperature and humidity conditions, which in the case of straw quilt meant 48 h' storage in an oven at 70 ± 2 °C and 50 ± 5% relative humidity (Fig. 2). The results show that the straw quilt had a length change of −0.38% (0.38 mm), a width change of −1.27% (0.64 mm) and a thickness change of −2.71% (0.26 mm). It is decreased in volume density was 3.8% and its volume density decreased by 6.4% (weight change was also taken into account).

3.6. Compressive behavior

Due to their low volume density, high porosity and compressibility, the failure of thermal insulation materials as a result of compressive stress is usually caused by excessive deformations (compression), so instead of compressive strength,

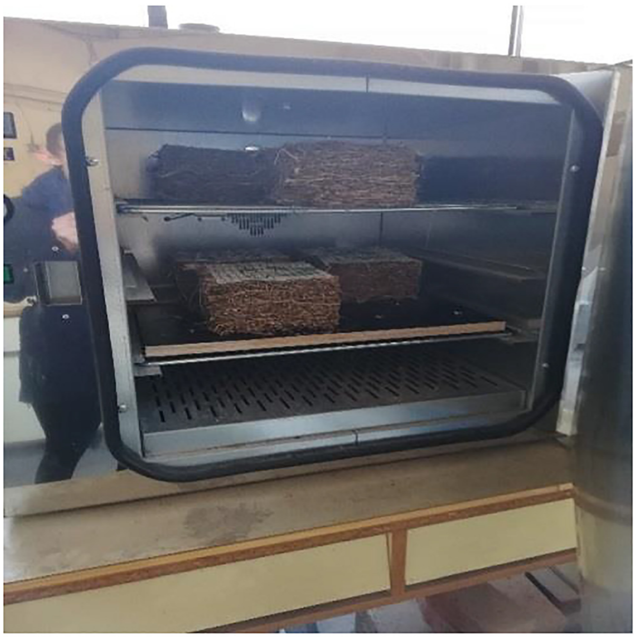

Fig. 2. Straw quilt samples in the drying oven (*photo*: Rebeka Ábrahám-Horváth)

compressive behavior can be determined, which means the compressive stress associated with 10% deformation.

Compressive behavior of straw quilt was tested on 20 × 20 cm samples according to EN 826:2013 standard [29]. Results showed that compressive strength of samples with jute mounting (i.e., with lower density) is 15.63 kPa (standard deviation: 4.42 kPa), while compressive strength of samples with linen mounting (i.e., with higher density) is 31.57 kPa (standard deviation: 6.64 kPa). These values remain below the compressive strength of most commercially available thermal insulation materials, but approach the compressive strength of some mineral wool products and some plastic foams. Based on the results, it can be stated that the installation of straw quilt is not practical if step-resistant insulation or even if a high compressive strength class is required (e.g., over rafters, terrace roofs).

3.7. Flexural strength

Method B of EN 12089:2013 standard [30] can be used to determine the flexural strength of the straw quilt, 15 × 30 cm specimens are required for the measurements.

Because of the extreme flexibility of the material, the deviation from the standard was that it was not necessary to load the samples to the point of failure due to bending. The load could only be increased until the specimen reached a deflection of 32.20 mm, at which point specimens suffered deformations from which the supporting edges were already not able to hold them. The flexural strength was 1.077 kPa (standard deviation: 0.153 kPa), which is extremely low compared to other thermal insulation materials.

3.8. Freeze-thaw resistance

The freeze-thaw resistance test was performed based on the requirements of EN 12091:2013 standard [31]. According to this, water-saturated samples with known compressive strength, stored under water for 28 days, should complete 300 freeze-thaw cycles (−20 and +20 °C) in the test chamber (Fig. 3) and after the required number of freeze-thaw cycles the change of compressive strength should be determined (the only deviation from the standard was that the water absorption lasted only 5 days instead of 28 days). The results showed that the compressive strength of samples with jute mounting decreased by 4.73% (from 15.63 to 14.89 kPa, standard deviation: 2.74 kPa) and compressive strength of samples with linen mounting decreased by 4.03% (from 31.57 to 30.30 kPa, standard deviation: 4.69 kPa). There were no visible changes and deformations in the samples, the material was not significantly damaged, so straw quilt can be considered as a freeze-thaw resistant material.

3.9. Summary of measurement results

Based on the measurement results it can be stated that the use of straw in building construction is not a novelty, but straw quilt, as a new, innovative thermal insulation material, can be unique in the Hungarian market of thermal insulation materials.

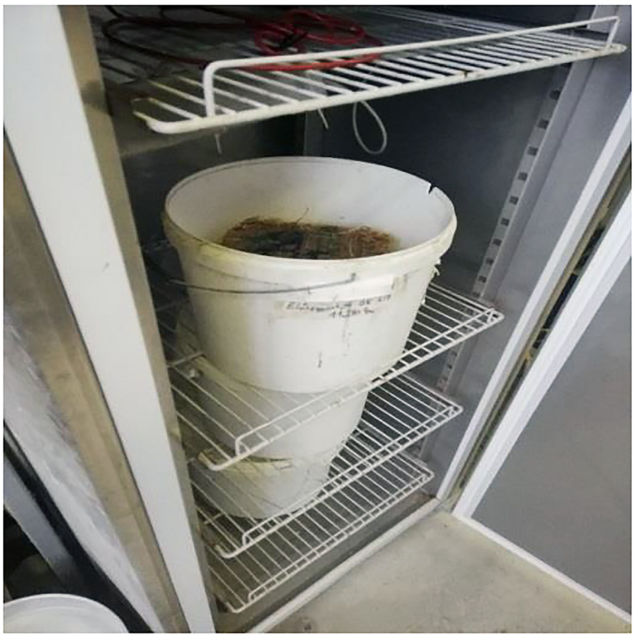

Fig. 3. Straw quilt samples in the freeze-thaw chamber (*photo*: Rebeka Ábrahám-Horváth)

Based on pre-market qualification tests, the product has become comparable with other common, widely used, and well-known thermal insulation materials (Table 2). Based on the data about the most important material properties (density, thermal conductivity, water absorption. compressive strength, flexural strength) of common thermal insulation materials [32, 33], it can be stated that straw quilt is mostly like to mineral wool (rock wool, fiberglass) and cellulose insulation. It can be particularly fixed, that its mechanical properties are significantly below those of other materials (expanded polystyrene, extruded polystyrene, polyurethane foam, foam glass, calcium silicate foam, cork, wood wool, fiberboards), but its thermal insulation ability (0.0401 W mK^{-1}), it is very close to that of mineral wool products, sheep wool, cellulose and hemp.

4. CONCLUSIONS

As a result of laboratory tests, the versatility of straw quilt thermal insulation was revealed, but at the same time its possible disadvantages were also highlighted. Its thermal conductivity is low enough to be used for insulating facades, attic spaces, ceilings and pitched roofs (e.g., between and under rafters). Its water resistance seems to be one of its most critical points, so it is only recommended to build in places where it is protected from moisture. Due to its low mechanical strength, it is mainly suitable for insulating places where it is not exposed to strong mechanical effects.

It would also be worthwhile to perform tensile strength, acoustic and water vapor diffusion tests to determine its sound insulation ability and water vapor permeability; however, it can be assumed that similarly favorable results are expected as in case of other natural materials (e.g., straw bale, hemp).

It would be advisable to test its fire resistance, although its fire resistance class would presumably E (normally flammable). There are no standards for testing its resistance to rodents and insects, but based on the preventive methods used in agricultural applications and in straw bale construction, some conclusions can be made about their protection (e.g., removal of seeds, embedding of metal mesh into the plastering).

Based on the performed tests, it can be stated that many properties of straw quilt approach, moreover in many cases exceed the material properties of common, commercially available thermal insulation product. Considering environmental and energy saving aspects (production, maintenance, recycling), it can be clearly stated that in many cases straw quilt can be an excellent alternative to artificial thermal insulation materials.

Table 2. The most important material properties of common thermal insulation materials compared to straw quilt

Material	Density ρ kg m^{-3}	Thermal conductivity λ W mK^{-1}	Water absorption w kg m^{-2}	Water absorption w %	Compressive strength σ_{comp} kPa	Flexural strength σ_{flex} kPa
expanded polystyrene	15–30	0.032–0.041	–	1–5[a]	30–300	50–150
extruded polystyrene	25–45	0.027–0.038	–	0.1–0.3[a]	150–700	100–300
polyurethane foam	30–100	0.022–0.030	–	1.3–3.0[a]	100–500	240–1,400
rock wool	20–200	0.035–0.045	1.0	–	15–80	5–20
fiberglass	10–150	0.035–0.045	1.0	–	15–80	3.5–20
foam glass	115–220	0.040–1.060	0.0	0	700–1,700	200–2,400
calcium silicate foam	115–300	0.040–1.065	2.5	–	200–500	800–1,000
cork	100–220	0.037–0.060	0.5	–	100–200	140–200
wood wool	350–700	0.070–0.090	5.0	–	150–200	400–2,400
fiberboard	30–270	0.040–0.090	1.0–2.0	–	40–200	120–200
hemp	20–90	0.039–0.050	4.2	20[b]	–	–
cellulose	20–200	0.035–0.045	1.0–3.0	–	15–80	–
sheep wool	20–70	0.035–0.045	12.0	33[b]	–	–
straw quilt	*86–103*	*0.039–0.041*	*1.3*	*300*	*15–30*	*1.08*

a: VV^{-1} %, b: m m^{-1} %

REFERENCES

[1] A. Chel and G. Kaushik, “Renewable energy technologies for sustainable development of energy efficient building,” *Alexandria Eng. J.*, vol. 57, no. 2, pp. 655–669, 2018.

[2] W. F. Lamb, T. Wiedmann, J. Pongratz, R. Andrew, M. Crippa, J. G. J. Olivier, D. Wiedenhofer, G. Mattioli, A. Al Khourdajie, and J. House, “A review of trends and drivers of greenhouse gas emissions by sector from 1990 to 2018,” *Environ. Res. Lett.*, vol. 16, no. 7, 2021, Paper no. 073005.

[3] 2021 Global Status Report for Buildings and Construction, United Nations Environment Program, Nairobi, Kenya, 2022.

[4] T. Horváth, “Modernization of modern buildings – case study on the main building of Széchenyi István University in Győr,” *Pollack Period.*, vol. 4, no. 3, pp. 67–78, 2009.

[5] Hungarian Energy and Public Utility Regulatory Authority (MEKH) (in Hungarian), Budapest, Hungary, 2021.

[6] M. Santamouris and K. Vasilakopoulou, “Present and future energy consumption of buildings-challenges and opportunities towards decarbonisation,” *e-Prime Adv. Electr. Eng. Electron. Energy*, vol. 1, 2021, Paper no. 100002.

[7] N. Pargana, M. D. Pinheiro, J. D. Silvestre, and J. Brito, “Comparative environmental life cycle assessment of thermal insulation materials of buildings,” *Energy Build.*, vol. 82, pp. 466–481, 2014.

[8] F. Pacheco-Torgal, “Introduction to the environmental impact of construction and building materials,” in *Eco-efficient Construction and Building Materials*, F. Pacheco-Torgal, L. F. Cabeza, J. Labrincha, and A. G. de Magalhães, Eds., Oxford, UK: Woodhead Publishing, 2014, pp. 1–10.

[9] Thermal insulation materials market analysis, Report, Coherent Market Insight, Seattle, WA, USA, 2020.

[10] J. Zach, J. Hroudová, J. Brožovský, Z. Krejza, and A. Gailius, “Development of thermal insulating materials on natural base for thermal insulation systems,” *Proced. Eng.*, vol. 57, pp. 1288–1294, 2013.

[11] M. Čuláková, I. Šenitková, and A. Paulíková, “Optimization of construction solutions for green building,” *Pollack Period.*, vol. 7, no. 3, pp. 33–44, 2012.

[12] M. Dovjak, M. Košir, L. Pajek, N. Iglič, D. Božiček, and R. Kunič, “Environmental impact of thermal insulations: How do natural insulation products differ from synthetic ones,” *IOP Conf. Ser. Earth Environ. Sci.*, vol. 92, 2017, Paper no. 012009.

[13] A. Déry, *Historical Materials Science* (in Hungarian). Budapest, Hungary: Terc Kiadó, 2000.

[14] P. Medgyasszay and Á. Novák, *Earth and Straw Architecture* (in Hungarian). Budapest, Hungary: Terc Kiadó, 2006.

[15] G. Minke and B. Krick, *Straw Bale Construction* (in Hungarian). Budapest, Hungary: Cser Kiadó, 2012.

[16] R. T. Bynum, *Insulation Handbook*. New York, USA: The McGraw-Hill Education, 2001.

[17] P. Neuberger and P. Kic, “A century of use of SOLOMIT thermal insulation panels,” *Energies*, vol. 14, no. 21, 2021, Paper no. 7197.

[18] W. Wasylciw, “Oriented split straw board – a new era in building products,” in *First International Conference on Ecological Building Network*, San Rafael, CA, USA, July 5–9, 2001, 2001, Paper no. 016076.

[19] Cs. Gyuricza, *Energy Crops, Biomass Production and Use* (in Hungarian). Gödöllő, Hungary: Szent István University, Institute of Crop Production, 2014.

[20] V. Nagy and A. Meggyes, “Waste or energy?” *Pollack Period.*, vol. 9, Supplement 1, pp. 17–21, 2014.

[21] Z. Tóth, T. Kismányoki, and T. Hermann, *Significance of Crop Rotation and Consideration for Teaching Land Qualification* (in Hungarian). Keszthely, Hungary: Hungarian Academy of Sciences, Centre for Agricultural Research, Institute for Soil Sciences, 2007.

[22] R. Horváth, “Beyond traditional thermal insulation - straw quilt thermal insulation as a new environmentally friendly alternative” (in Hungarian), BSc Thesis, Széchenyi István University, Győr, Hungary, 2021.

[23] *EN 1602:2013*, Thermal insulating products for building applications, Determination of the apparent density, CEN, Bruxelles, 2013.

[24] *EN 12667:2001*, 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, CEN, Bruxelles, 2001.

[25] *EN 1609:2013*, Thermal insulating products for building applications, Determination of short term water absorption by partial immersion, CEN, Bruxelles, 2013.

[26] *EN 12087:2013*, Thermal insulating products for building applications, Determination of long term water absorption by immersion, CEN, Bruxelles, 2013.

[27] *EN 1603:2013*, Thermal insulating products for building applications, Determination of dimensional stability under constant normal laboratory conditions (23 °C/ 50% relative humidity), CEN, Bruxelles, 2013.

[28] *EN 1604:2013*, Thermal insulating products for building applications, Determination of dimensional stability under specified temperature and humidity conditions, CEN, Bruxelles, 2013.

[29] *EN 826:2013*, Thermal insulating products for building applications, Determination of compression behavior, CEN, Bruxelles, 2013.

[30] *EN 12089:2013*, Thermal insulating products for building applications, Determination of bending behavior, CEN, Bruxelles, 2013.

[31] *EN 12091:2013*, Thermal insulating products for building applications, Determination of freeze-thaw resistance, CEN, Bruxelles, 2013.

[32] M. Pfundstein, “Types of insulation” (in German), in *Detail Praxis – Thermal Insulation Materials (Basics, Materials, Applications).* München, Germany: Institute for International Architecture-Dokumentation Ltd., pp. 17–57, 2007.

[33] D. Bozsaky, *Thermal Insulation Materials in Building Construction* (in Hungarian). Budapest, Hungary: Terc Kiadó, 2017.