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Composite material for thermal insulation based on moss raw material

Aliaksandr Bakatovich [a], Florindo Gaspar [b,*]

[a] Polotsk State University, Blokhin Str., 29, Novopolotsk 211440, Belarus
[b] CDRSP, School of Technology and Management, Polytechnic Institute of Leiria, Campus 2, Morro do Lena – Alto do Vieiro, Apartado 4163, 2411-901 Leiria, Portugal

HIGHLIGHTS

- Thermal insulation compositions based on *Sphagnum* moss were studied.
- Better properties were obtained for mixed compositions of moss and rye straw.
- Inner structure of the rye straw and reed explain the resulting properties.
- Ecological insulating materials of moss, straw, reed and liquid glass were developed.

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ABSTRACT

The demand for thermal insulation materials composed of sustainable raw materials remains a challenge. The substances used in the manufacture of thermal insulation materials may also, under certain conditions, have a beneficial effect on the insulated surfaces, the environment, and the human or animal body, in particular by the ability to absorb moisture and biocidal properties. Ecological insulation materials of vegetable raw materials are increasingly widespread. Most of the time, these materials are made from flax, hemp or wood fibres, agglomerated with a binder. The objective of this work was to determine the possibility of using *Sphagnum* moss as a fibre in thermal insulation panels. To carry out this study, several compositions were developed for thermal insulation boards based on moss, rye straw and reed, using liquid glass as a binder. The specimens were tested for thermal conductivity, and strength to compression and bending. Best results were achieved on panels of moss and straw with thermal conductivity of 0.044–0.046 W/(m.K) at a density of 156–190 kg/m^3, without shrinking during drying and a compression strength between 0.20 and 0.21 MPa. Electronic microscopy of rye straw and reed stems made it possible to examine the presence of outer and inner parts in the structure, which affect the thermal and strength characteristics.

With the use of natural raw materials from plants and agricultural production residues, an effective and ecologically safe rigid board insulation was obtained, which has biocidal properties and has no analogues in the market for the construction of thermal insulation materials.

1. Introduction

Reducing energy costs associated with the thermal comfort of buildings requires selection of suitable insulation materials. The essential properties of thermal insulation include, but are not limited to, thermal conductivity, vulnerability to puncture, adaptability and flexibility to the construction site, mechanical strength, fire protection, smoke emission during fire, robustness, durability, resistance to ice/thaw cycles, water resistance, costs and impact on the environment [1].

The impact of the construction materials on the environment has been an increasing concern, which must to be considered along with the essential strength and thermal properties. It is known that the environmental impact of thermal insulation materials can be improved [2]. Vegetable fibres, such as straw, flax, corn, hemp, wood, coconut and sunflower, are one type of raw materials that can suit this concern, given their economic, energy and environmental sustainability, and have nowadays more and more applications in the construction industry [3]. The scientific interest on these type of materials has led to significant amount of research published recently [4].

The interest on vegetable fibres increases when considering the use of the wastes generated on the processing of agricultural products, namely on the manufacture of thermal insulating materials,

* Corresponding author.
E-mail addresses: a.bakatovich@psu.by (A. Bakatovich), florindo.gaspar@ipleiria.pt (F. Gaspar).

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which allows their revaluation, instead of disposal [5]. In addition, the agro-wastes have the potential to create efficient materials, regarding the thermomechanical, energetical and cost performances, along with effective sustainability [6].

Ecological insulation materials of vegetable raw materials may be made of, for example, flax fibre, hemp [78], cotton [9], bamboo [10], rice husks [11], rice straws [12], cotton stalk fibres [9], cotton stems [13], sunflower seeds [14,15], and others, agglomerated with an appropriate binder. These natural materials are made in the form of carpets, plates or rolls, and can be applied in a wide variety of applications, including insulation of walls, roofs, floors and ceilings.

Some authors have also developed materials that result from the combination of various fibre plants. For example, Korjenic et al. [16] developed a new thermal insulation material based on jute, flax and hemp and Bakatovich et al. [17] achieved promising results using rye straw and flax boon.

There are several examples of product implementation of this type in the market. One of the well-known and environmentally friendly thermal insulation materials is "Geokar" used for the construction of green homes. This material, composed of 60% peat, is manufactured in Russia.

The use of natural materials on insulation boards has advantages over petroleum by-products because of lower harm to the environment, the embodied carbon and nitrogen are prevented from being released into the environment as harmful gases and ashes, natural materials have no threats to human or environmental health, and the embodied energy and life-cycle costs of natural materials are considerably lower [18]. In addition, the economic and environmental impact can be reduced through the use of local natural materials, and can decrease the use of oil based and not renewable sources [19]. The environmental viability of some agro-residue based thermal insulation boards, like hemp based materials [20,21] and rice husk [11], is already known. However, few information about their environmental impact is available for this type of products given its recent stage of development or commercial implementation.

This study is focussed on the application of *Sphagnum* moss in the production on thermal insulating plates. The experience in the use of *Sphagnum* moss in various spheres of human activity has been known since the eleventh century. Moss is used in medicine and as biomonitor for environmental assessment [22,23]. *Sphagnum* genus includes about 350 species growing mainly in the Northern Hemisphere [24] and is widespread from the mountains of the tropics to the Arctic and subarctic zones, growing mainly where the increased humidity of air prevails.

The properties of the *Sphagnum* moss include: ecological compatibility [25], medicinal (bactericidal) properties [26], nonsusceptibility to decay and low thermal conductivity [22]. Considering the given set of positive qualities, the use of moss for plate heat insulation material is very interesting. In this sense, the use of *Sphagnum* moss as the main component of the fibre for a thermal insulation material was the main focus of this work, taking into account the current requirements of a product of this type. In addition, the use liquid glass as a binder was evaluated, as it shows to be heat and fire resistant [27]. These materials were used for the production of thermal-insulation plates with economic profit while ensuring environmental safety of the climate and human beings.

2. Materials and testing methods

2.1. Raw materials and preparation of specimens

The fibre used in the manufacture of insulation boards was *Sphagnum* moss, which is a natural plant material, found in vast areas of temperate latitudes. Sphagnum moss is a fibrous plant with a length of about 50 to 100 mm. After being harvested the moss was first dried in a chamber at a temperature of 40 to 50 °C for 6 to 8 h and then cut into lengths of 10 to 20 mm.

Rye straw and common reed (*Phragmites communis*) were also used in combination with moss to give rigidity to the insulation material and reduce retraction during the drying of the plates. The straw and reed stems were cut into pieces in the form of tubes with 15 to 20 mm long.

Liquid sodium silicate (liquid glass) was used as the binder for preparation of the insulation boards, corresponding to the standard GOST 13078-81 [28], and having silicate module of 2.9, pH 11 to 12, viscosity of 0,0194 $(N{\cdot}s)/m^2$, density of 1.45 to 1.47 g/cm^3, and thermal conductivity of 0.23 W/(m·K).

In the preparation of the specimens all components of the experimental compositions were weighed according to the specimen size and composition. The binder and fibre were mixed, and then evenly placed in the mould and covered with a lid. A moulding pressure of 0.2 MPa was then applied and kept for 5 to 6 h, and then removed and dried for 6 to 7 h in a chamber at a temperature of 40 to 50 °C.

In a first test series, only the moss was used as a fibre in the preparation of thermal insulation material. It was decided to make 18 different compositions, varying the quantities of moss between 100 g and 300 g and liquid glass between 200 and 400 g.

In a second phase of the work, the reed and straw were mixed with the moss, obtaining a mixed material of two components (moss and reed or moss and straw) with 220 g of total mass of the mixed fibres. Reed and straw were introduced in amounts of 20% to 50% of the total mass. The amount of liquid glass changed between 200 and 400 g.

2.2. Testing methods

Before the compression and bending tests, the specimens were kept for at least 6 h at a temperature of 23 ± 5 °C and relative humidity of 50 ± 5%, according to the requirements of the standard EN 826 [29], until they reach the equilibrium moisture content.

2.2.1. Compression strength

Compression strength at 10% of linear strain was determined on specimens in the form of cubes with an edge size of 100 mm, according to the standard EN 826 [29], on five specimens for each composition. Compression load was applied at a constant rate of $0.1 \times d$ per minute, where d is the thickness of the test specimen.

2.2.2. Bending strength

Bending strength was determined in accordance with standard EN 12089 [30], on five specimens for each composition, having the form of beams with 30 mm thick, 40 mm wide and 250 mm long. A three-point bending test was used, having cylinders with 80 mm in diameter for supports and load, over the entire width of the specimens. Supports were spaced 200 mm between them, and at a distance of 25 mm from the end surface of the specimens. The load was applied at a speed of 10 mm/min.

For this test, specimens corresponding to mixtures of 400 g of liquid glass with 220 g of fibres were used. In the samples of the second phase, the composition corresponds to the use of 50% of reed or straw.

2.2.3. Density of the specimens

Five cube specimens for each composition, with an edge size of 100 mm, were used for the density measurements. First, the specimens were weighed after drying to constant weight at a temperature of 50 °C, and then the volume was calculated after measuring the length, width and thickness of the specimens.

2.2.4. Bulk density of raw materials

The bulk density of chopped straw or reed was calculated, determining the weigh placed into a container with a volume of 10 L (0.01 m^3), without compaction and only shaking.

2.2.5. Determination of thermal conductivity

The thermal conductivity of slabs measuring 250 × 250 × 30 mm was measured according to the heat flow meter method, as described on the standard EN 12667 [31], on five specimens for each composition. First, the specimens were dried to constant weight at a temperature of 50 °C. Then, the thermal conductivity (λ_{25}) of the specimens was determined using the equipment ITP-MG4 «250», where the surface temperatures of the heating and refrigerator plates was 40 °C and 10 °C, respectively. During the test, specimens were kept in a sealed chamber of the device. The mass of specimens was measured before and after the test.

2.2.6. Electronic microscopy analysis

To explain the mechanisms of the influence of the reed and rye straw structure on the results obtained on the physical and mechanical characteristics of thermal insulation plates, the microstructure of the stems in the cross and longitudinal sections was studied using the "JSM-5610 LV" electron microscope.

3. Results and discussion

3.1. Electronic microscopy

The microstructure of the stems in the cross and longitudinal sections of reed and rye straw was studied.

3.1.1. Rye straw specimen

The outer part of the stem of the rye is 250–350 μm thickness and consists of capillaries 5–40 μm in diameter, separated in the longitudinal section by partitions 1–3 μm thick, spaced 150–500 μm (Figs. 1 and 2). Capillaries of the outer part ensure the strength of the stem in the longitudinal and cross section. In this case, the capillaries can undergo elastic or plastic deformations, while maintaining their integrity.

The inner part of the stem of the rye consists of capillaries, reminiscent of honeycombs with a diameter of 40–90 μm in cross section (Fig. 1). In a length of 50–100 μm, the capillaries are separated by thin transparent partitions with a thickness of less than 0.5 μm (Fig. 2) and form cells that are close to cylindrical shape. The thickness of the inner part reaches 300–450 μm. Due to its effective structure, the inner part of the stem provides higher thermal insulation properties than the outer part.

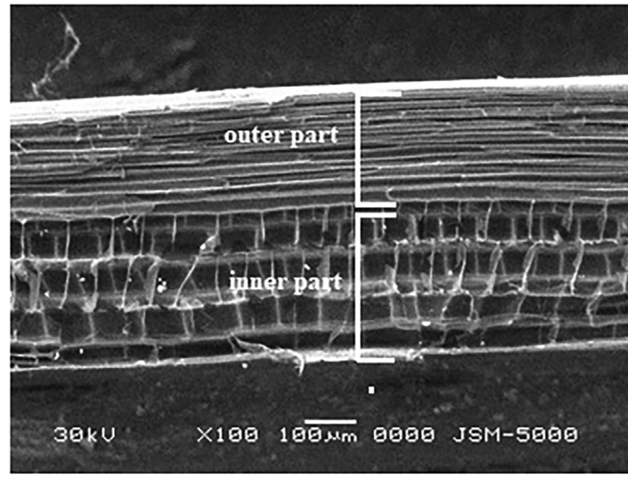

Fig. 2. Longitudinal section of the rye stem (100x magnification).

3.1.2. Reed specimen

The outer part of the reed is 250–400 μm thick and has a dense structure. The diameter of the capillaries is 10–20 μm, increasing to the inner part (Figs. 3 and 4). A hollow channel with a diameter of 4–8 μm is located at the centre of each outer capillary, having wall thicknesses of 3–6 μm.

Tubes form a resilient and rigid framework in the longitudinal section of the reed stem. The thickness of the walls of the outer reed capillaries is 2–3 times higher than the thickness of the walls of the capillaries of the outer part of the straw. At the same time, the diameters of the capillaries of the outer part of reed are 2–4 times smaller than the size of the maximum diameter of straw capillaries. The capillary frame ensures the integrity of the plant under deformations caused by bending forces from winds. However, in the cross section, the fibre orientation structure in the longitudinal section is unable to undergo significant elastic and plastic deformation, and with the application of small cross forces, an instant brittle failure of the stem occurs. This disadvantage does not allow to obtain the fibres from reeds with a length of less than 10 mm when cutting the stem.

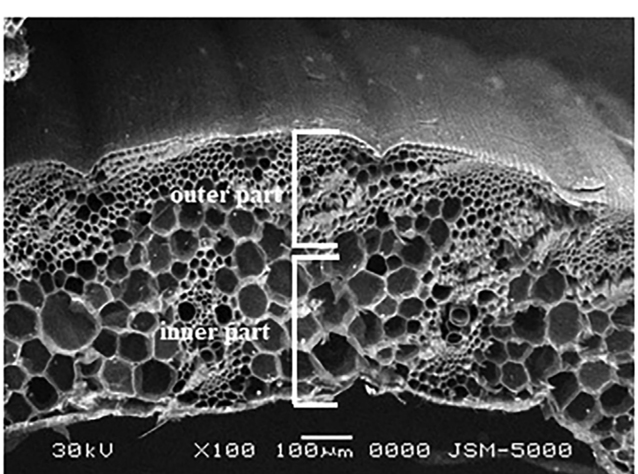

Fig. 1. Cross section of the rye stem (fragment, 100x magnification).

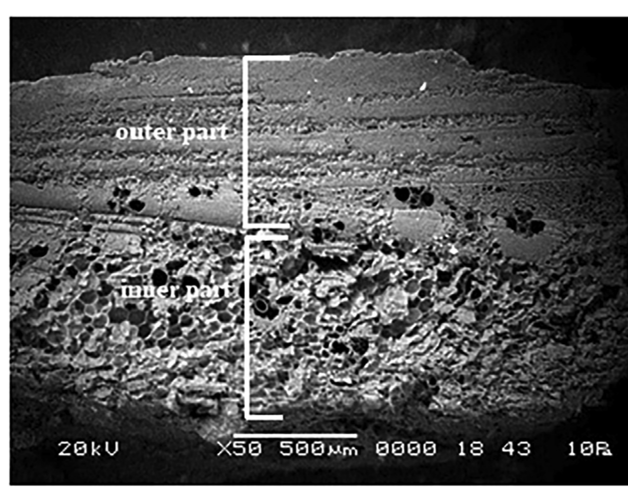

Fig. 3. Cross section of the reed stem (fragment, 50x magnification).

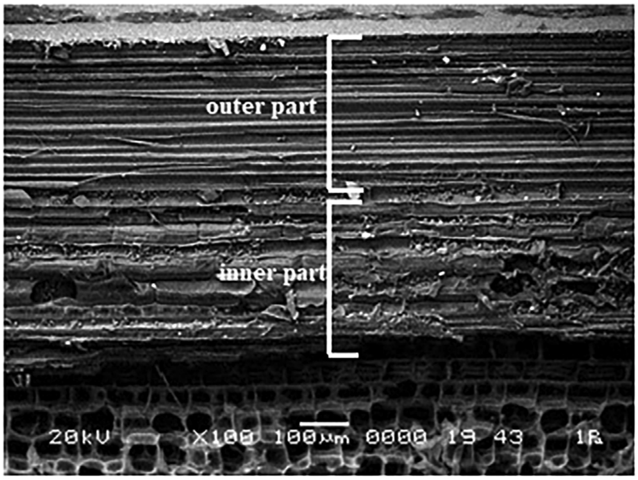

Fig. 4. Longitudinal section of the reed stem (100x magnification).

The inner part of 300–400 µm thick consists of a main layer of capillaries, having 20–40 µm diameter separated by transverse partitions spaced of 100–150 µm (Figs. 3 and 4). The thickness of the walls of the capillaries is 2–3 µm.

Thus, the inner part of the stem provides the thermal insulation properties as the rye straw. However, because of the smaller (in 2–4.5 times) transverse dimensions of the cells and with a larger thickness of the capillaries (5–6 times thick), the reed provides poorer thermal insulation properties in comparison with rye straw. This conclusion can be confirmed by the coefficients of thermal conductivity equal to 0.067 and 0.05 W/(m·K) for reed plates and straw bales, respectively [32,33].

From the results of electron microscopy, it is concluded that with the same thickness of the stalk wall, the reed has a denser microstructure than straw. The 2–6 times higher capillary wall thickness and the decrease of 2–4.5 times in the diameters of the reed stalk capillaries as compared with the straw microstructure give the reason for the 1.6 times higher bulk density of the chopped reed as compared with the chopped straw.

3.2. Results of the density, thermal conductivity and shrinking

The results of the tests obtained with the moss specimens are shown in Table 1.

The results show that, for a fixed amount of binder (e.g. 300 g), an increase in the fibre consumption of 100 g to 220 g (samples 1.12 and 1.9) leads to an increase in density by 26% and a reduction in thermal conductivity by 31%. However, a further increase in fibre consumption from 220 to 300 g (samples 1.9 and 1.7) increases the thermal conductivity by 42% from 0.04 to 0.068 W/(m·K). An increase in the amount of liquid glass also leads to an increase in thermal conductivity (Fig. 5). Thus, when comparing the characteristics of samples 1.3 and 1.9, it is noted that the addition of 100 g of binder causes an increase in thermal conductivity and in the density by 15% and 19%, respectively, for the same amount of moss. Comparing the samples 1.3 and 1.15, the thermal conductivity increased by 28% and the density by 37%.

Thus, an increase in the amount of moss (above 220 g in this case) and in the liquid glass increases the thermal conductivity and the density of the plate. These results are probably due to the fact that the increase of the liquid glass consumption allows the increase of the thermal bridges through the layers of the binder. With a consumption of 220 g of moss, it is possible to achieve an optimized densified structure that attenuates the free movement of air heat through the insulation, which guarantees the preservation of the integrity of the cellular microstructure. The further increase in the density of the thermal insulation material possibly leads to the crushing and densification of the cellular microstructure, causing destruction of the cell walls. As a result, it is believed that there is heat loss in the fibre material. The best thermal conductivity results were obtained in compositions 1.3, 1.9 and 1.15 with different binder intakes, which is due to the formation of an optimal moss structural system that blocks the passage of air through the insulation. In this case, the internal cellular microstructure of the stem and leaves of moss remains as intact as possible.

After the insulation plates were manufactured, considerable shrinkage deformations along the length and width of 7 to 8 mm were observed corresponding to about 6% of the dimensions of the mould. When mixed with liquid glass, the water is absorbed by dead moss cells, due to its hygroscopicity, which should lead to its increase in volume. Thus, the size of moss fragments increases, leading to a significant expansion. During drying, the water evaporates from the cells, and the moss decreases in size, which leads to shrinkage deformation.

In a second step of the work, in order to obtain a more rigid material and reduce shrinkage, an additional component was introduced, the reed, in the form of chopped tubes from 1 to

Table 1
Physical characteristics of samples composed of moss.

Sample reference	Mix composition (g)			Average physical characteristics*		
	Moss	Liquid Glass	Water	Density (kg/m^3)	Thermal Conductivity (λ_{25}) W/(m·K)	Sample dimensions (cm)
1.1	300	400	175	300 (5.5)	0.075 (0.005)	24.4 × 24.4 × 3
1.2	260		160	285 (5.9)	0.060 (0.004)	24.4 × 24.4 × 3
1.3	220		145	265 (6.5)	0.047 (0.004)	24.4 × 24.3 × 3
1.4	180		130	250 (6.4)	0.050 (0.004)	24.3 × 24.3 × 3
1.5	140		115	225 (6.8)	0.056 (0.003)	24.3 × 24.2 × 3
1.6	100		100	200 (7.0)	0.063 (0.004)	24.2 × 24.2 × 3
1.7	300	300	175	255 (5.9)	0.068 (0.003)	24.4 × 24.3 × 3
1.8	260		160	235 (6.2)	0.053 (0.004)	24.3 × 24.3 × 3
1.9	220		145	215 (6.3)	0.040 (0.004)	24.3 × 24.2 × 3
1.10	180		130	200 (6.8)	0.045 (0.004)	24.2 × 24.2 × 3
1.11	140		115	180 (7.0)	0.051 (0.003)	24.2 × 24.2 × 3
1.12	100		100	160 (7.8)	0.058 (0.003)	24.2 × 24.1 × 3
1.13	300	200	175	205 (7.0)	0.059 (0.005)	24.3 × 24.3 × 3
1.14	260		160	185 (7.4)	0.047 (0.004)	24.3 × 24.3 × 3
1.15	220		145	170 (7.9)	0.034 (0.003)	24.3 × 24.2 × 2
1.16	180		130	155 (8.2)	0.040 (0.003)	24.2 × 24.2 × 3
1.17	140		115	140 (8.0)	0.046 (0.004)	24.2 × 24.1 × 3
1.18	100		100	120 (8.4)	0.052 (0.005)	24.1 × 24.1 × 3

* Numbers between brackets correspond to the standard deviation

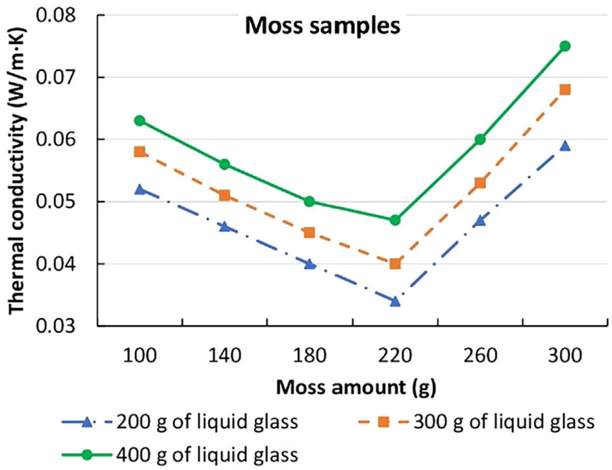

Fig. 5. Thermal conductivity of moss samples.

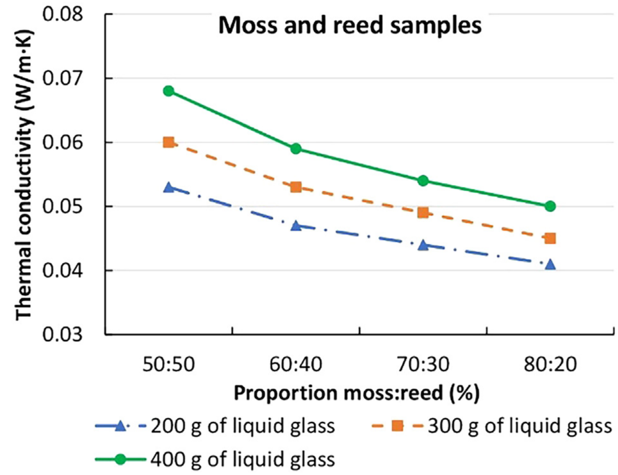

Fig. 6. Thermal conductivity of moss and reed samples.

2 cm in length. In the composition of a mixed aggregate material, the reed tubes should create an interconnected structure. For the total mass of the mixed aggregate, the mass corresponding to the compositions of the moss samples 1.3, 1.9 and 1.15 (Table 1) was adopted because they lead to the lowest thermal conductivity. The reed was introduced in amounts of 20 to 50% of the total aggregate mass.

The results of the tests obtained with the samples prepared with moss and reed are presented in Table 2.

It is found that for a given amount of binder, the increase in the proportion of reed in the mixture leads to an increase in the thermal conductivity of the slabs (Fig. 6). Thus, for example, the introduction of reed in the amount of 50% of the total mass of the aggregate (sample 2.5) causes an increase in thermal conductivity compared to sample 2.8, by 33%, from 0.045 to 0.06 W/(m·K). In addition, an increase in the thermal conductivity is observed with the increase in the amount of binder. For example, for compositions 2.3 and 2.11 with an equal aggregate composition, an increase in the mass of liquid glass in 200 g (test specimen 2.3) led to an increase in thermal conductivity by 23%. In general, the thermal conductivity of the two-component materials (Table 2) is higher than that of the single component compositions (Table 1) for the same mix proportion aggregate:binder. The sample 2.12 with the highest amount of moss with a density of 166 kg/m^3 has a thermal conductivity of 0.041 W/(m·K), which is 21% higher than that of a single component with the same amount of binder (sample 1.15, Table 1).

The amount of reed introduced does not ensure the formation of a sufficiently rigid structure to eliminate shrinking in all compositions. In addition, a portion of reed stalks is divided into smaller particles during mixing, leading to higher compactness of the plate. The uniform distribution of the reed tubes in the plates was also more difficult to achieve. As a result, the heat fluxes in the material structure lead to an increase in thermal conductivity. The lowest coefficient of thermal conductivity of the moss and reed plates is 0.041 W/(m·K), obtained in sample 2.12, having a density of 166 kg/m^3 for a mixing ratio of 80:20.

The shrinking was eliminated only in sample 2.1 with the maximum amount of binder and a proportion of 50:50 of moss and reed. In the other compositions, shrinking decreased by 3 to 5 mm compared to moss plates.

Instead of reed, another component, rye straw, was used as chopped tubes with dimensions between 10 and 20 mm. The results of the tests of the insulation material resulting from the mixture of moss and straw are shown in Table 3.

The results obtained allow to evaluate the influence of the composition (proportion of the aggregate and the amount of binder in the mixture) in the thermal conductivity, being verified that it is lower to the one obtained for the material prepared based on the mixture of moss and reed (Fig. 7). A decrease in the thermal insulation properties of the material over compositions with a single component aggregate (Table 1) and an improvement in performance compared to moss and reed plates (Table 2) were obtained.

Table 2
Physical characteristics of samples composed of moss and reed.

Sample reference	Mix composition (g)					Average physical characteristics*		
	Moss	Reed	Proportion moss:reed (%)	Liquid Glass	Water	Density (kg/m^3)	Thermal conductivity (λ_{25}) W/(m·K)	Sample dimensions (cm)
2.1	110	110	50:50	400	100	228 (6.1)	0.068 (0.004)	25.0 × 24.9 × 3
2.2	132	88	60:40		115	231 (5.4)	0.059 (0.005)	24.8 × 24.8 × 3
2.3	154	66	70:30		130	234 (5.6)	0.054 (0.003)	24.6 × 24.6 × 3
2.4	176	44	80:20		145	235 (5.9)	0.050 (0.004)	24.5 × 24.4 × 3
2.5	110	110	50:50	300	75	194 (6.9)	0.060 (0.005)	24.9 × 24.8 × 3
2.6	132	88	60:40		90	195 (6.5)	0.053 (0.003)	24,8 × 24.7 × 3
2.7	154	66	70:30		105	198 (7.1)	0.049 (0.004)	24.6 × 24.5 × 3
2.8	176	44	80:20		130	200 (7.4)	0.045 (0.004)	24.4 × 24.4 × 3
2.9	110	110	50:50	200	75	160 (7.6)	0.053 (0.003)	24.7 × 24.7 × 3
2.10	132	88	60:40		90	163 (8.1)	0.047 (0.004)	24.7 × 24.6 × 3
2.11	154	66	70:30		105	165 (7.8)	0.044 (0.003)	24.5 × 24.3 × 3
2.12	176	44	80:20		130	166 (8.3)	0.041 (0.004)	24.3 × 24.3 × 3

* Numbers between brackets correspond to the standard deviation

Table 3
Physical characteristics of samples composed of moss and straw.

Sample reference	Mix composition (g)					Average physical characteristics*		
	Moss	Straw	Proportion moss:straw (%)	Liquid Glass	Water	Density (kg/m^3)	Thermal conductivity (λ_{25}) W/(m·K)	Sample dimensions (cm)
3.1	110	110	50:50	400	100	225 (6.3)	0.063 (0.005)	25.0 × 25.0 × 3
3.2	132	88	60:40		115	226 (6.1)	0.058 (0.004)	25.0 × 25.0 × 3
3.3	154	66	70:30		130	227 (5.8)	0.054 (0.003)	25.0 × 25.0 × 3
3.4	176	44	80:20		145	226 (5.9)	0.051 (0.005)	25.0 × 25.0 × 3
3.5	110	110	50:50	300	75	191 (6.8)	0.056 (0.005)	25.0 × 25.0 × 3
3.6	132	88	60:40		90	192 (6.7)	0.050 (0.003)	25.0 × 25.0 × 3
3.7	154	66	70:30		105	190 (6.5)	0.046 (0.004)	25.0 × 25.0 × 3
3.8	176	44	80:20		130	191 (6.4)	0.043 (0.004)	24.8 × 24.8 × 3
3.9	110	110	50:50	200	75	157 (8.0)	0.049 (0.003)	25.0 × 25.0 × 3
3.10	132	88	60:40		90	156 (7.9)	0.044 (0.004)	25.0 × 25.0 × 3
3.11	154	66	70:30		105	155 (8.1)	0.040 (0.003)	24.8 × 24.8 × 3
3.12	176	44	80:20		130	156 (7.8)	0.037 (0.003)	24.7 × 24.6 × 3

* Numbers between brackets correspond to the standard deviation

For example, with a maximum amount of moss and a binder consumption of 200 g (sample 3.12), the thermal conductivity is 0.037 W/(m·K), which is 9% higher than the value of the sample 1.15 (Table 1) and 11% lower for the 2.12 sample of the moss and reed mixture (Table 2).

The increase of the amount of straw in the composition lead to an increase in the thermal conductibility. For example, in compositions 3.5 and 3.8 (Table 3), with an equal mass of liquid glass, an increase in the amount of straw in the composition leads to a 30% thermal conductivity increase, from 0.043 W/(m·K) to 0.056 W/(m·K).

The addition of 200 g of binder with an equal proportion of the components in the mixture increases the density of the plates, like for samples 3.10 and 3.2 which gave densities of 156 kg/m^3 and 226 kg/m^3, respectively, corresponding to an increase of 45%, and the thermal conductivity of sample 3.2 is 0.058 W/m·K corresponding to an increase of 32%.

In the comparison between the results obtained with straw and with reed as components of mixed aggregate, it should be noted that the bulk density of the straw is 50 kg/m^3, which is 1.6 times smaller than the value of reed, equal to 79 kg/m^3.

With equal mass of components, the straw occupies 2 times more volume in the aggregate mixture. By forming plates based on a mixture of moss and straw, a rigid specimen of crushed straw stems is obtained, filling the void with a dense moss structure, which prevents the free flow of air through the insulation structure. The resulting structural system provides a lower thermal conductivity, and better resistance than the previous ones.

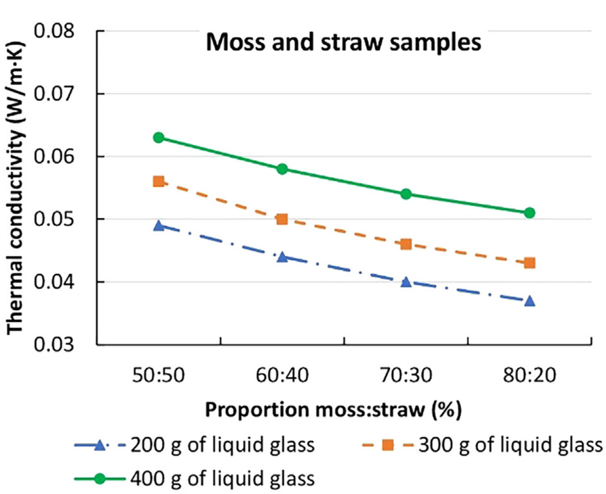

Fig. 7. Thermal conductivity of moss and straw samples.

When using a mixture of moss and straw, significant changes in the reduction in shrinking were observed. The shrinkage of the plates during drying in the longitudinal direction was 2 to 3 mm in the compositions with the least amount of straw and binder (test pieces 3.8, 3.11 and 3.12). There was no shrinkage in the specimens of the other compositions. The lowest thermal conductivity is 0.037 W/(m·K) in sample 3.12 (Table 3). A decrease in the density of the material was also observed compared to the plates based on the mixture of moss and reed, as for example, the density of sample 3.8 (Table 3) was 191 kg/m^3, which is 9 kg/m^3 lower than that of sample 2.8 (Table 2).

3.3. Results of the mechanical strength tests

3.3.1. Compression strength

The test results for the moss fibre test samples for the 10% deformation compression strength are shown in Table 4.

Analysis of the data shows that an increase in the amount of fibre increases the compression strength of the material (Fig. 8). A similar dependence is observed with a change in the consumption of the binder. Thus, for an equal amount of fibre there is a strength increase with increasing liquid glass.

In the second phase of the work the test specimens were prepared based on fibres of moss and reed tubes, as well as moss and straw. The results of the compression tests are presented in Tables 5 and 6, and in Figs. 9 and 10.

Table 4
Compression strength of samples composed of moss.

Sample number	Mix composition (g)		Compression strength (MPa)*
	Moss	Liquid Glass	
1	140	220	0.21 (0.014)
2	120		0.18 (0.013)
3	100		0.15 (0.009)
4	80		0.11 (0.070)
5	140	160	0.17 (0.010)
6	120		0.14 (0.010)
7	100		0.10 (0.006)
8	80		0.08 (0.007)
9	140	100	0.12 (0.007)
10	120		0.09 (0.006)
11	100		0.06 (0.004)
12	80		0.05 (0.004)

* Numbers between brackets correspond to the standard deviation

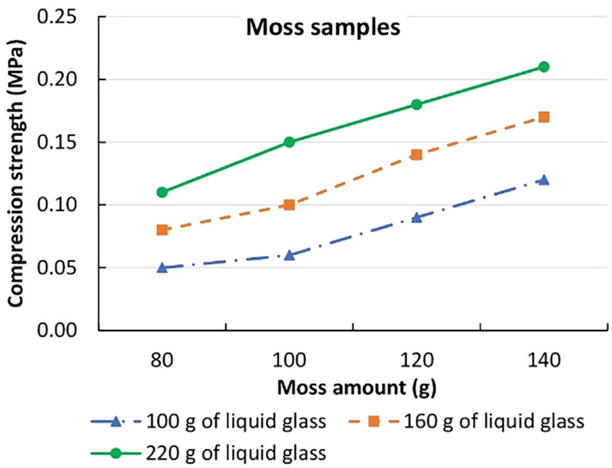

Fig. 8. Compression strength of moss samples.

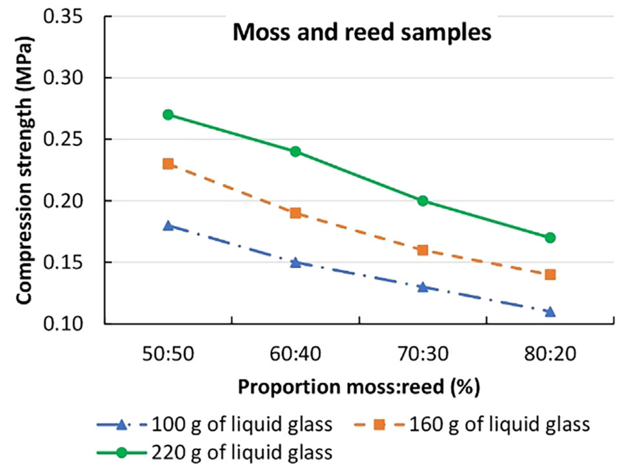

Fig. 9. Compression strength of moss and reed samples.

The analysis of the results allows to conclude that when replacing part of the moss by reed or straw a strength increase is obtained. Thus, the compression strength at 10% deformation of sample 1 (Table 6) based on moss and straw is 0.30 MPa, which is 43% higher than that of specimen 1 of moss fibre (Table 4). The highest strength of the test cubes with aggregates of moss and reed is 0.27 MPa (sample 1, Table 5), which is 29% higher than the composition of moss and 19% lower than the value of sample 1 of moss and straw (Table 6).

It was also found that, with an equal amount of binder, increasing the amount of reed or straw in the total mass of the aggregate leads to increased strength of the samples. Similarly, the increase in the consumption of binder in the same proportion of the aggregates leads also to an increase of strength.

The obtained data allows to conclude that, for all compositions, the compression strength of the moss and straw mixtures is higher than for moss and reed samples. The rigid structure created by the straw allows not only to eliminate shrinking deformations but also

Table 5
Compression strength of samples composed of moss and reed.

Sample number	Mix composition (g)			Proportion moss:reed (%)	Compression strength (MPa)*
	Moss	Reed	Liquid glass		
1	60	60	220	50:50	0.27 (0.016)
2	72	48		60:40	0.24 (0.015)
3	84	36		70:30	0.20 (0.016)
4	96	24		80:20	0.17 (0.012)
5	60	60	160	50:50	0.23 (0.012)
6	72	48		60:40	0.19 (0.014)
7	84	36		70:30	0.16 (0.010)
8	96	24		80:20	0.14 (0.011)
9	60	60	100	50:50	0.18 (0.012)
10	72	48		60:40	0.15 (0.011)
11	84	36		70:30	0.13 (0.009)
12	96	24		80:20	0.11 (0.009)

* Numbers between brackets correspond to the standard deviation

Table 6
Compression strength of samples composed of moss and straw.

Sample number	Mix composition (g)			Proportion moss:straw (%)	Compression strength (MPa)*
	Moss	Straw	Liquid glass		
1	60	60	220	50:50	0.30 (0.020)
2	72	48		60:40	0.29 (0.022)
3	84	36		70:30	0.25 (0.018)
4	96	24		80:20	0.22 (0.012)
5	60	60	160	50:50	0.28 (0.021)
6	72	48		60:40	0.24 (0.015)
7	84	36		70:30	0.21 (0.014)
8	96	24		80:20	0.19 (0.012)
9	60	60	100	50:50	0.23 (0.014)
10	72	48		60:40	0.20 (0.015)
11	84	36		70:30	0.18 (0.015)
12	96	24		80:20	0.16 (0.012)

* Numbers between brackets correspond to the standard deviation

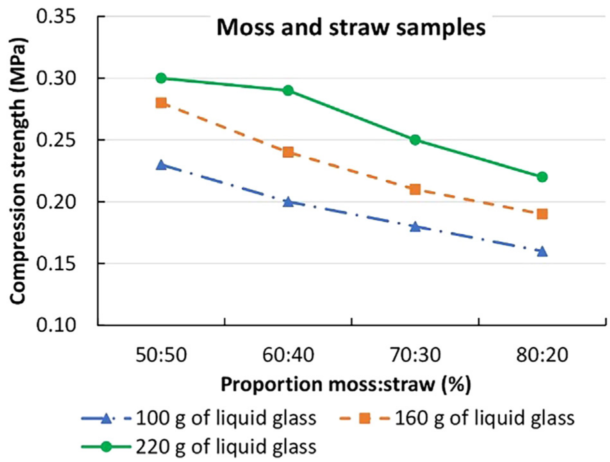

Fig. 10. Compression strength of moss and straw samples.

Table 7
Bending strength of samples.

Mix composition (g)				Bending strength (MPa)*
Moss	Reed	Straw	Liquid Glass	
220	–	–	400	0.08 (0.008)
110	110	–		0.14 (0.008)
110	–	110		0.26 (0.013)

* Numbers between brackets correspond to the standard deviation

to support external loads, which is probably due to the shape of the straw tubes with the configuration of hollow cylinders which remain even after the moulding pressure.

3.3.2. Bending strength

The results of the bending tests showed a significant increase in the strength of the moss and straw plates (Table 7) compared to samples composed only of moss or by moss and reed. Thus, the average bending strength of the moss and straw compositions is 0.26 MPa, which is 1.9 times higher than the composite composition based on moss and reed and 3.2 times higher than the value of the sample based of a single component.

The significant increase in bending strength due to straw indicates that the structure of the straw tubes leads to higher bending and compression forces during the mechanical tests. Thus, the spatial structure system of straw tubes, with the empty space filled with compressed moss is the most ideal structure of the insulation, which provides high physical and mechanical parameters of the insulation material.

4. Conclusions

A study was carried out to optimize the composition of a thermal insulation material based on *Sphagnum* moss, rye straw and reed, bonded with liquid glass.

The increase in aggregate and liquid glass consumption leads to an increase in the density of moss insulation materials by 1.3 to 1.4 times, an increase in the compression strength of 1.9 to 4.2 times and an increase in thermal conductivity from 1.4 to 1.7 times.

The high physical and mechanical characteristics of the thermal insulation material are due to the formation of a spatial structure from straw tubes with the filling of the empty space with moss as well as a fine mesh microstructure of straw and moss.

The new thermal insulation material developed based on natural raw materials of agricultural origin and agricultural production provides a thermal conductivity of 0.044 to 0.046 W/(m.K) at a density of 156 to 190 kg/m^3, without shrinking during drying and a compression strength between 0.20 and 0.21 MPa.

Differences on physical and strength characteristics between plates using rye straw and plates using reed stems have a strong relation with the different structures of the outer and inner parts of these stalks.

With the use of natural raw materials from moss and agricultural production residues, an effective and ecologically safe rigid plate was obtained, which has biocidal properties and has no analogues in the market for the construction of thermal insulation materials.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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