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Thermal insulation materials based on eucalyptus bark fibres

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ABSTRACT

The civil construction industry significantly contributes to global energy consumption, prompting a shift towards sustainable practices to mitigate environmental impacts throughout the building lifecycle. Traditional thermal insulation materials, such as polyurethane foam and mineral wool, are cost-effective but fail to meet environmental safety standards. In this context, plant-based materials have emerged as an eco-friendly alternative for thermal insulation, with agroforestry waste offering a sustainable raw material source. This waste is abundant and often improperly disposed of, thus utilizing it can reduce the environmental footprint of the agroforestry sector. This study focuses on developing thermal insulation plates using eucalyptus bark fibres, with some samples incorporating wheat straw. Various methods were employed: sodium silicate as a binder in some samples, while others used a binder-free method involving pulping bark in lye, and some included carbonised eucalyptus bark. The primary goal was to evaluate properties like thermal conductivity and moisture sorption. The electron microscope analysis provided insights into the microstructure of the fibres, explaining their insulation mechanisms. The thermal conductivity of the plates ranged from 0.036 to 0.059 W/(m·K) at a density of 80–220 kg/m^3, influenced by the preparation processes (mechanical grinding, lye pulping, carbonization) and binder use. Eucalyptus bark fibre samples demonstrated low moisture sorption for plant-based materials, with 9.4–14.5 % at 60 % relative humidity and 21.6–38.5 % at 97 % relative humidity. Additionally, the samples showed high resistance to fungal growth when wet, suggesting good durability for thermal insulation applications. Overall, the study's results indicate that eucalyptus bark fibres hold significant promise as a sustainable raw material for producing thermal insulation, offering an environmentally friendly alternative to traditional materials while enhancing the durability and effectiveness of insulation in construction.

1. Introduction

The civil construction industry plays a significant role in the global economy but also has substantial environmental impacts. The sector is a major consumer of resources and energy, generating a considerable amount of waste and greenhouse gas emissions [1]. As the demand for buildings and infrastructure continues to grow, there is an urgent need to explore alternative construction materials that are sustainable and environmentally friendly [2]. In addition to the search for sustainable construction materials, the energy efficiency of buildings is crucial for promoting sustainability in the civil construction industry. Thermal insulation materials play a fundamental role in improving the energy efficiency of buildings by reducing the transfer of heat through the building envelope, thus decreasing the need for energy for heating and cooling [3]. Traditional thermal insulators, such as EPS and XPS, are widely utilised due to their low thermal conductivity, with thermal conductivity values between 0.025 and 0.040 W/(m·K). However, their production relies on non-renewable raw materials, such as petroleum, and they exhibit extremely slow decomposition rates, making recycling challenging [4]. Another commonly used material is glass wool, which has a thermal conductivity of around 0.030 and 0.046 W/(m·K). Its manufacturing process involves high temperatures and the use of chemicals in, generating toxic waste and fine particles that can be harmful to human health [5]. On the other hand, polyurethane foam, has a thermal conductivity of 0.025 to 0.046 W/(m·K), while widely used, has been associated with environmental susceptibility due to residual catalysts used in its production [6].

An alternative to conventional non-sustainable materials is the use of

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forestry residues as raw materials for thermal insulation in construction. These natural materials offer excellent thermal properties and can be derived from renewable resources, making them environmentally friendly alternatives for insulation applications [2]. The effective improvement in thermal insulation properties stems from the low thermal conductivity and fibrous attributes of most organic materials when integrated into the external envelope of buildings [7]. Organic materials found in nature exhibit distinct physical characteristics, such as a high specific heat capacity and increased sensitivity to moisture. These properties set them apart from conventional silicate materials [8]. Additionally, the use of forestry residues in insulation materials provides an opportunity to address waste management in the forestry sector. By reusing these materials, the construction industry can contribute to the circular economy, reducing the amount of waste sent to landfills and promoting the efficient use of resources [9]. Furthermore, it diminishes reliance on traditional building materials, which have a high carbon footprint, given that approximately 82 % of the total embodied carbon is contained in the materials incorporated into the building [10]. In addition to environmental benefits, incorporating forestry residues into insulation materials aligns with the concept of utilising local resources to promote sustainability [11]. By integrating locally sourced materials, such as eucalyptus bark fibres, into construction products, the construction industry can reduce its dependence on non-renewable resources and minimise the environmental impact associated with material transportation [12]. This approach supports the principles of sustainable development and contributes to the resilience of local economies.

The potential use of forestry residues in the development of thermal insulation materials has garnered attention in recent years. Within this context, the use of tree bark as a raw material for thermal insulation materials has been widely explored. Bark is recognized as a naturally optimised material that insulates and protects trees [13]. For instance, tree bark plays a role in safeguarding against fires [14], and the thermal insulation attributes of cork, a distinct component of bark found in oak species, is widely recognised and highly esteemed [15]. Bark is the protective layer of trees, defending its vascular cambium from various potential threats, including mechanical damage, frost, heat, fires and fungal attacks [16,17].

In the study by Pásztory and Ronyecz [18], bark from five common tree species in Europe, namely black locust, a poplar clone, larch, spruce, and Scotch pine, was investigated. Their insulation characteristics were compared to traditionally used insulation materials measuring the heat flow. No bonding materials were used. Instead, the chips were loosely scattered in the measuring box. The results suggest that the thermal insulation capacity of chipped tree bark is comparable to that of commonly used insulation materials. In the study by Kain et al. [19], thermal insulation panels made from larch, pine, spruce, fir, and oak tree bark were investigated. Different resins (urea formaldehyde, melamine formaldehyde, Quebracho, Mimosa) were used as a binder. The lowest thermal conductivity measured was 0.059 W/(m·K), and all investigated bark species were found to be suitable for insulation panel production. Gößwald et al. [20] explored the potential of low-density insulation boards made from spruce bark fibres. These boards had varying densities and fibre lengths and were manufactured using a wet process. The results indicated that the thermal insulation properties of bark fibre insulation boards can achieve thermal conductivity ranging from 0.044 W/(m·K) (at a density of 164 kg/m^3) to 0.063 W/(m·K) (at 276 kg/m^3), with density significantly influencing the results. In broad terms, incorporating bark into bio-composite panels for thermal insulation offers green alternatives to conventional insulation materials.

Eucalyptus pulp production generates large amounts of waste in the form of leaves, branches, roots, bark and wood chips. Bark accounts for 10–12 % of the total mass of waste. Consequently, there are 10–12 tons of bark per 100 tons of pulp [21–23]. The annual natural discharge of eucalyptus bark adds to the amount of material available for recycling and use as a structural raw material to produce thermal insulation [24]. Thus, eucalyptus bark is of interest as an available multi-tonnage raw material to produce thermal insulation materials.

Eucalyptus trees are extensively cultivated for their rapid growth and high wood yield [25]. Eucalyptus form the largest expanse of non-native forests in Europe, predominantly situated in the Iberian Peninsula, covering approximately 1.5 million hectares. These forests are primarily cultivated for pulpwood, managed as even-aged monocultures, and undergo coppicing in 10–12 year rotations cycles [26]. Its importance is not only evident in the vast occupied area and the profitable nature of its cultivation but also in the macroeconomic significance it holds, serving as the raw material for the paper pulp industry [27]. The bark, typically regarded as a byproduct, can be processed into fibres and has potential to be used in thermal insulation materials for construction [26], using residual material and providing an alternative to conventional insulation materials [28]. Some studies were already conducted on the use of eucalyptus bark for insulation material production. In the study by Becerra et al. [29], eucalyptus bark was utilised to craft thermal insulation panels, employing phenolic resin as a fibre binding agent. They demonstrated that eucalyptus bark serves as an effective thermal insulator, with values of thermal conductivity ranging from 0.05 to 0.07 W/(m·K). Barth et al. [30] developed a novel processing technology for eucalyptus bark fibres, enabling the production of competitive and high-performance fibre insulation materials compared to conventional insulation materials. They produced fibre mat and board samples with a thickness of 50 mm, achieving thermal conductivity values between 0.042 and 0.044 W/(m·K). Silva et al. [31] investigated the properties of composite panels using eucalyptus bark with four different types of resins (phenol-formaldehyde, melamine-formaldehyde, tannin-formaldehyde, and urea-formaldehyde). Tests were conducted to assess the physicomechanical properties of the various compositions, including density and thermal and acoustic performance. The study results indicate superior acoustic insulation compared to polystyrene foam and suitable thermal performance for applications as insulating material.

Based on the literature review regarding the use of eucalyptus bark as a thermal insulator, this research aims to deepen the understanding of the behaviour of the material through carbonisation technology and explore new results by incorporating sodium liquid glass as a binding agent. The primary objective is to analyse various physical and mechanical properties, including the examination of microstructure, granulometric composition, density, thermal conductivity coefficient, and sorption moisture, and observe the influence of each property on the overall performance of the material. The overarching goal is to expand knowledge regarding the materials' behaviour and their effectiveness as a thermal insulator.

2. Materials and testing methods

2.1. Materials

2.1.1. Fibres

Eucalyptus bark (*lat. Eucalýptus*) (Fig. 1) collected from eucalyptus groves near the city of Leiria (Portugal) was used as a structure-forming material for thermal insulation.

To obtain fibres, the bark was mechanically processed using an Elikor 1 mill grinder (Fig. 2). The particle size at the outlet was controlled

Fig. 1. Harvested eucalyptus bark (before grinding).

Fig. 2. Grinding of eucalyptus bark on an Elikor 1.

by a sieve with a 5 mm mesh diameter installed in the grinder. After grinding, the fibrous mass was subjected to fractionation through sieves with 0.16–5 mm mesh diameter.

In a separate series of samples, the structure-forming material was a mixture of bark and wheat straw fibres. Wheat straw was pre-processed on an Elikor 1 mill grinder. The straw particle fraction used in the studies were 5–8 mm long, 1–1.5 mm wide and less than 1 mm thick. The amount of straw incorporated in the mixtures was from 15 % to 25 %.

2.1.2. Binder

Sodium liquid glass, produced by JSC "Domanovsky Industrial and Commercial Plant", was used as a binder in the moulding of experimental thermal insulation slabs. Sodium liquid glass is produced according to the requirements of GOST 13078–81 [32]. Liquid glass was modified to ensure water resistance by adding 5 % of the solid binder mass made up of lime and gypsum, which additionally ensures the incombustibility of the insulation in case of fire in the building. Liquid glass was used as a binder for the manufacture of plate specimens, which has good adhesion to vegetable substrates. In addition, liquid glass can be considered an environmentally friendly product, as it releases only water vapor when heated. Moreover, when dispersed in soil or water, it quickly depolymerises, breaking down into silicon compounds that are indistinguishable from those naturally occurring in the environment [33,34]. Sodium liquid glass was also selected for its fire-resistant properties, as eucalyptus bark has high combustibility, and the liquid glass helps mitigate this risk by ensuring the non-flammability of the composite material.

2.2. Testing methods

Five different sample series were prepared. The first consisted solely of eucalyptus bark in various fractions. The second series incorporated wheat straw fibres with eucalyptus bark fibres. The third series used eucalyptus bark using the lye pulping method. The fourth series combined eucalyptus bark fibres with liquid glass as a binder, and the fifth series used carbonized eucalyptus bark fibres. The preparation details for each series are explained below.

2.2.1. First series of samples

In the first stage of the research, the thermal conductivity coefficient of bark fibres of different fractions (Fig. 3) was measured in the bulk state without binder component. The required volume of bark fibres was poured and evenly distributed in the measuring chamber of the device "ITP-MG4".

2.2.2. Second series of samples

In the second series of samples, a two-component structure-forming material based on fractionated fibres of eucalyptus bark and chopped wheat straw (Fig. 4) was used as thermal insulation. The density and thermal conductivity coefficient were determined similarly to the first stage.

2.2.3. Third series of samples

The third series of samples was used to study the possibility of obtaining thermal insulation slabs without binder component using the method of pulping bark in lye. First, the preparation and dosage of components was carried out. Wood ash was sieved with a mesh diameter of 0.16 mm. After, an aqueous lye solution was prepared by pouring 5 litres of water and 0.5–0.6 litres of fractionated wood ash into a 6-liter metal cylinder and then setting it on a sand bath. The resulting mixture was heated to 100 °C and boiled until soapy and homogeneous mixture was obtained. The required amount of bark was immersed in the resulting solution and continued to be boiled for 4–6 hours until

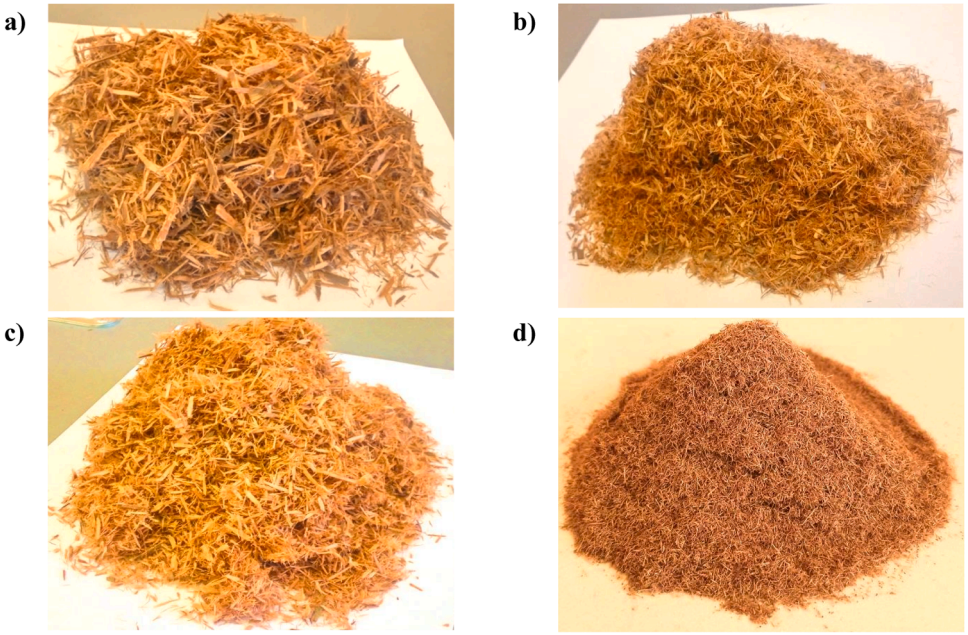

Fig. 3. Different fractions of eucalyptus bark fibre after grinding: a) coarse; b) medium; c) fine; d) ultrafine.

Fig. 4. Mixture of eucalyptus bark fibres and chopped wheat straw: a) coarse fraction; b) medium fraction; c) fine fraction.

softening. Then the liquid solution was poured off and the bark was washed from ash residues.

The following three technological solutions were used for moulding the raw material mixture:

1. The obtained bark plates were laid horizontally in the mould layer by layer, forming layers with minimal gaps between the plates. Each subsequent layer was laid perpendicular to the previous layer (Fig. 5);
2. The bark plates were divided into narrow strips 3–4 mm wide, after which the mixture of the strips was placed in a mould and evenly distributed (Fig. 6);
3. The bark was broken into individual fibres using a construction mixer to obtain a homogeneous mass. The resulting mixture was evenly placed in a mould (Fig. 7).

The mixture placed in the mould was covered with a lid and pressed. The slab samples were kept in the mould for 24 hours at 20±2 °C, and dried to constant weight for 48 hours in a desiccator at 45–50 °C. Then, the average density and thermal conductivity coefficient of the slabs were determined.

Fig. 5. Slab of horizontally stacked strips of bark (1st variant).

Fig. 6. Slab of narrow multidirectional strips of bark (2nd variant).

Fig. 7. Slab of bark fibres crushed with a construction mixer (3rd variant).

2.2.4. *Fourth series of samples*

To obtain samples of slabs of the fourth series, bark fibres were mixed with liquid glass (Fig. 8). All components were weighed beforehand. First, the fibres were moistened with a sprayer and mixed. Liquid glass, previously diluted with water to 25 % solution, was introduced into the moistened mixture using a spray gun. After uniform distribution of liquid glass and its mixing to a homogeneous mass, the slab was moulded. Then the mould was covered with a lid and placed under the press.

Fig. 8. Plate based on eucalyptus bark fibres (medium fraction) and liquid glass.

The lid was lowered to the required slab height and fixed in the loaded state at a pressure of 0.01 MPa for 6 hours. Then the slab was dried for 10 hours in a drying cabinet at a temperature of 45–50°C to constant mass. Density and thermal conductivity coefficient of the slabs were determined after their cooling down to the temperature of 20±2 °C.

2.2.5. Fifth series of samples

At the fifth stage of research, the thermal conductivity coefficient of carbonised eucalyptus bark fibres, with and without a binding component, was determined. The carbonisation process was carried out in a SNOL 60/300 LFN drying cabinet at a temperature of 300 °C. Eucalyptus bark fibres of ultrafine fraction (Fig. 9) were poured into a metal cylinder (volume of 3 litres) without sealing and closed with a metal lid to prevent the penetration of air into the container. The closed cylinder was placed in a drying cabinet. The cabinet door was closed tightly, and the heat was turned on. Within 30 minutes the temperature reached 300 °C, after which a gradual smoke emission from the chamber vent began. Then at intervals of 30 minutes the smoke emission or absence of smoke was recorded. After the cessation of smoke emission, a control interval of 30 minutes was waited, if there was no smoke, the carbonisation process was considered complete. The carbonisation time was 3 hours.

The method of electron microscopy was used to determine the main parameters of the bark microstructure, influencing the thermal insulation properties of the material. For this purpose, samples of eucalyptus bark were examined on a JSM-5610 LV electron microscope.

The main physical parameters of thermal insulation slabs - density and humidity - were measured in accordance with GOST 17177–94 [35].

The thermal conductivity coefficient of the experimental compositions was determined according to EN 12667 [36] using 250×250×30 mm samples on the device "ITP-MG4" between warm (40 °C) and cold plates (10 °C) to determine the coefficient of thermal conductivity (λ).

Five samples were tested in each series.

The sorption moisture content of the material samples was determined according to the STB EN 12088 [37] standard using desiccators.

3. Laboratorial test results

3.1. Electronic microscopy

The microstructure of eucalyptus bark and its fibres was studied using electron microscope images (Figs. 10–15). The outer surface of the whole bark (before grinding) is divided into separate microcells with the presence of a large number of microcracks with a width of 2–5 μm, which determines the unevenness of relief and roughness of the surface (Fig. 10). The microcellular structure is formed by the first layer of regenerating bark cells. During the regeneration of the bark, the cells of the first layer die off and form a strong protective shell of the bark. Microcracks on the surface appear as a result of tensile forces arising in the bark during the growth of the eucalyptus trunk.

On the inner side, the bark has a cellular structure, and the surface is represented by destroyed vascular tubes (Fig. 11). Destruction occurs along the contact layer of vessels in the adjacent layers to the wood when the bark is torn off during the grinding process. As a result, a structure is formed with a chaotic arrangement of round-shaped voids with dimensions of 10–40 μm and a sharp drop in the microrelief of the surface.

In cross-section, eucalyptus bark is a porous structure formed of hollow vascular tubes 15–50 μm in size (Figs. 12, 13). In the end section, the tubes have different shapes from round to rounded irregular shapes. The wall thickness of the tubes is 0.5–1 μm. The tubes are separated along their length by transverse partitions 0.5–1 μm thick at 100–200 μm intervals.

During bark grinding, fibres of different thicknesses were obtained. The study of the obtained fibres made it possible to establish that the thickness of fibres depends on the number of vascular tubes in the formed bundle after bark grinding. In this case, the fibre may consist of a single vascular tube as in Fig. 14 and have a thickness of 25 μm or consist of a bundle of vascular tubes 80–250 μm in width (Fig. 15). The fibres have a pronounced rough surface obtained in the process of grinding the bark during deformation and destruction of the microstructure.

Comparison of experimental data on determination of bark and fibre microstructure parameters with microscopy results obtained earlier by the authors of the study on plant raw materials (rye, wheat straw, flax shove and fibres, cane) [38–41] confirm the possibility of using Eucalyptus bark as a structure-forming material for insulation.

Fig. 9. Slab made of carbonised eucalyptus bark fibres of ultra-fine fraction.

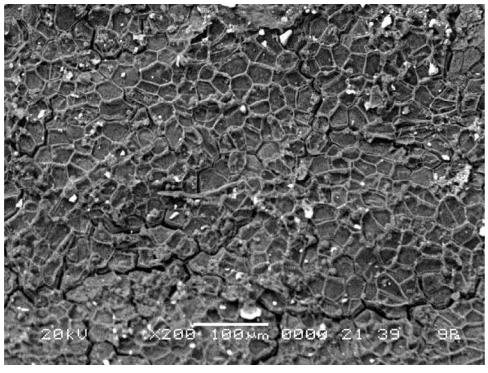

Fig. 10. The outer surface of eucalyptus bark before grinding (200x magnification).

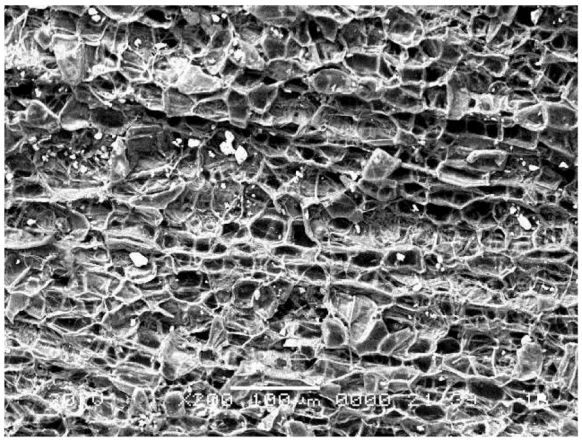

Fig. 11. Inner surface of eucalyptus bark before grinding (200x magnification).

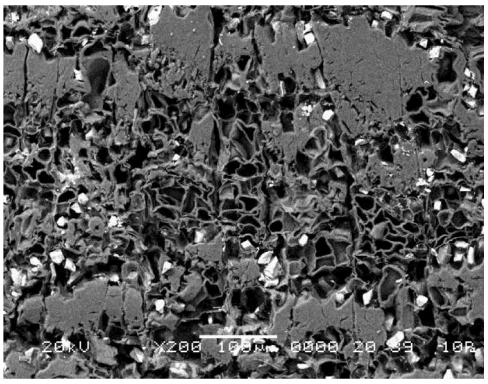

Fig. 12. Transverse section of eucalyptus bark (fragment, 200x magnification).

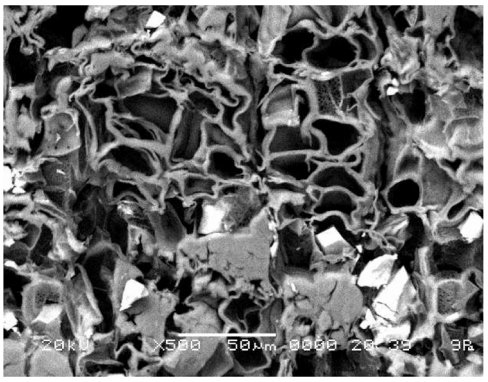

Fig. 13. Transverse section of eucalyptus bark (fragment, 500x magnification).

3.2. Granulometric composition of Eucalyptus bark fibres

The main objective of the research was to determine the influence of the fraction and density of ground bark on the thermal conductivity of fibrous mass without binder.

In the process of bark grinding, at natural moisture content of 5–6 %, strong amount of fine particles (< 0.16 mm) was observed. The number of fine particles amounted to 28.1 % of the total mass of the material. To eliminate this problem, the bark was pre-wetted to a moisture content of 20–30 %. After that, the fine particles intensity decreased to 18.1 % and the number of medium-sized fine fibres increased.

After grinding, the fibrous mass was fractionated using a sieve with mesh size 0.16–5 mm in diameter. The crushed bark particles of

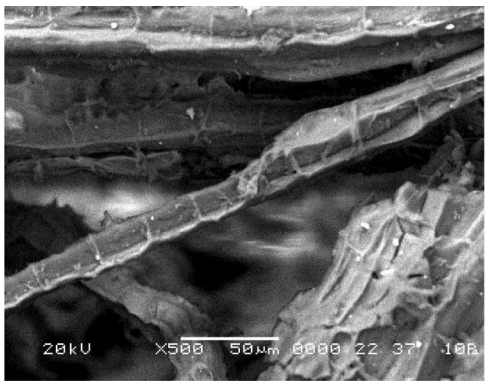

Fig. 14. Fibres after grinding of eucalyptus bark (500x magnification).

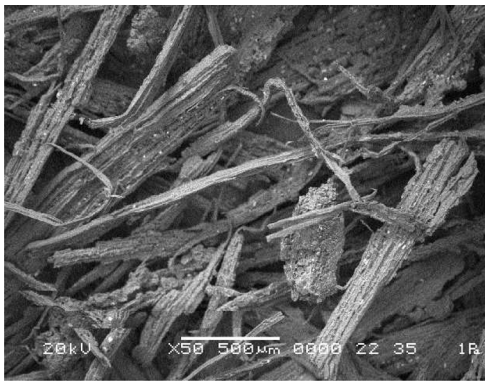

Fig. 15. Fibres after grinding of eucalyptus bark (50x magnification).

0.16–5 mm in size were divided into four fractions according to the cross-sectional size (width) of the fibre: coarse (2.5–5 mm), medium (1.25–2.5 mm), fine (0.63–1.25 mm) and ultrafine (0.16–0.63 mm).

In addition to the size in cross section, the fibres differed in length. The length of fibres of the coarse, medium, fine and ultrafine fractions correspond to 15–40 mm, 8–15 mm, 5–8 mm and 2–5 mm, respectively. The results of the granulometric analysis of the ground fibre mixture are shown in Table 1.

According to the results of granulometric analysis, it is established that at grinding of moistened bark, the formation of fine particles is reduced by 1.54 times in relation to the mass of bark fine particles screening without moistening. For fractions 0.63–5 mm the increase in the content of ground bark fibres differs insignificantly and is within 6.5–7.4 %. Significant increase in the percentage content (by 26.9 %) is noted for crushed bark fibres of the fraction 0.16–0.63 mm.

The obtained data show that pre-moistening of bark, allows to reduce the formation of fine particles by 35.4 %, to increase the total mass of fibres obtained during grinding by 13.8 % and in particular to increase the content of ultrafine fibres up to 31.6 %.

3.3. Thermal conductivity coefficient of eucalyptus bark fibres

To study the density and thermal conductivity coefficient, the fractionated fibres were poured into the chamber of the device "ITP-MG4", covered with a lid and measured the parameters (Fig. 16). It should be noted that the fibres have a high ability to bond to each other, forming a cohesive structure that retains its shape.

As a result, the dependences of the thermal conductivity coefficient variation on the average fibre density by fractions were obtained (Fig. 17). When varying the density within 50–220 kg/m^3, the thermal conductivity coefficient varies in the range from 0.042 to 0.062 W/(m·K). The results obtained in this study are close to the thermal

Table 1
Granulometric composition of the bark after grinding.

Bark moisture, %	Fraction content, %				
	2.5–5 mm	1.25–2.5 mm	0.63–1.25 mm	0.16–0.63 mm	< 0.16 mm
5–6	15.4	16.8	14.9	24.9	28.1
20–30	16.4	17.9	15.9	31.6	18.1

Fig. 16. Coarse eucalyptus bark fibres stacked in the "ITP-MG4" chamber.

conductivity coefficient values found in research conducted by other authors who also studied the potential use of bark fibres as thermal insulation material, which ranged from 0.042 to 0.07 W/(m·K) [29,30].

For the coarse fraction of eucalyptus fibres, at a density of 50 kg/m^3 the thermal conductivity coefficient is 0.062 W/(m·K). With a gradual increase in the average density and reaching 140 kg/m^3, the thermal conductivity coefficient decreases by 19.4 % to 0.05 W/(m·K). An increase in the thermal conductivity coefficient by 12 % to 0.056 W/(m·K) is observed at the highest density of 220 kg/m^3.

When studying the medium fibre fraction, it was found that for the minimum density of 50 kg/m^3 the thermal conductivity coefficient corresponds to 0.053 W/(m·K). Decrease of the thermal conductivity coefficient up to 0.049 W/(m·K) is registered at the density of 70 kg/m^3. This thermal conductivity coefficient is also maintained for the structure with a density of 90 kg/m^3. For the maximum average density of 220 kg/m^3 the increase in the thermal conductivity coefficient amounted to 20.4 % and reached the value of 0.058 W/(m·K).

The thermal conductivity of fine eucalyptus fibres with a density of 50 kg/m^3 is 0.054 W/(m·K). The minimum thermal conductivity corresponds to 0.051 W/(m·K) at a density of 90 kg/m^3. Subsequent gradual increase in the density of the fibre structure contributes to an increase in the thermal conductivity coefficient. So, at a density of 220 kg/m^3 the thermal conductivity coefficient of eucalyptus fibres is 0.061 W/(m·K), i.e. 19.6 % higher than the minimum value.

The best thermal conductivity coefficient values were recorded for ultrafine fibres. So, at density 70–90 kg/m^3 the coefficient of thermal conductivity amounted to 0.043 W/(m·K). At density increase up to 120 kg/m^3, the coefficient of thermal conductivity practically does not change and is equal to 0.044 W/(m·K). The lowest value of thermal conductivity coefficient was recorded at density equal to 140–160 kg/m^3 and corresponds to 0.042 W/(m·K). Further increase in the average density leads to a gradual increase in the thermal conductivity coefficient by 9.5 % and reaches 0.046 W/(m·K) at a density of 220 kg/m^3.

The thermal conductivity of insulating materials generally depends on the amount of air trapped within the structure. Air is an excellent thermal insulator. As the material's density increases, the space for air diminishes, resulting in lower insulation. However, the relationship is not linear. At certain densities, compaction can optimise the amount of trapped air, reducing thermal conductivity up to a point before it begins to increase again at higher densities [42].

The observed variation in thermal conductivity with density follows a trend that aligns with known principles of insulation. At lower densities, the higher proportion of air trapped between fibres contributes to better insulation, resulting in lower thermal conductivity. As density increases, however, the amount of trapped air decreases, causing the thermal conductivity to rise. This relationship between density and thermal conductivity indicates the presence of an optimal density range, where the air-to-fibre ratio minimises thermal transfer. The ultrafine fibres particularly demonstrated this effect, reaching their lowest thermal conductivity values within the 140–160 kg/m^3 density range. Such behaviour suggests that beyond a certain compaction, the increased material density begins to reduce the air pockets crucial for insulation, thus raising the thermal conductivity.

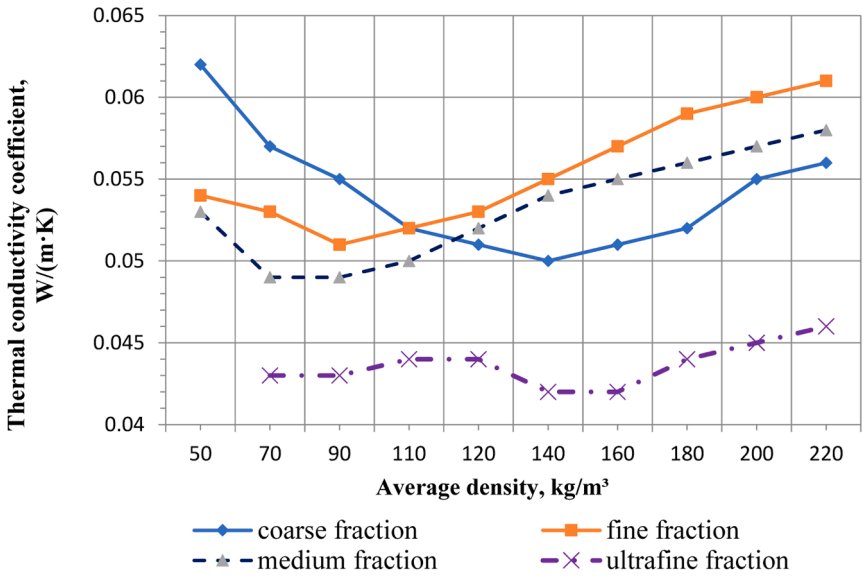

Fig. 17. Dependence of thermal conductivity coefficient on the density of eucalyptus bark fibres of different fractions.

Furthermore, the arrangement of fibres also affects thermal conductivity. Ultrafine fibres can settle more densely and uniformly, as they have a greater surface area relative to their volume. However, this does not necessarily mean their thermal conductivity will be higher, as it may result in greater adhesion between the fibres, creating a more stable structure less prone to heat transfer. The larger surface area can also reduce the formation of thermal bridges, which are preferential pathways for heat transfer. The combination of these factors contributes to a structure that effectively impedes heat propagation, resulting in better thermal insulation performance [42].

3.4. Thermal conductivity coefficient of eucalyptus bark fibres with chopped wheat straw

Based on the obtained results, further investigation was done on a two-component structure-forming material consisting of eucalyptus bark fibres of different fractions and chopped wheat straw. Straw is an agricultural by-product consisting of dry stalks or stems of wheat, which remain in the field after the grain has been harvested. The main structural components are cellulose, hemicelluloses, and lignin. This waste has been widely used as an alternative material for thermal insulation in buildings [43]. The thermal conductivity index of the wheat straw was 0.046 W/(m·K) at a density of 80 kg/m^3 [44]. The chopped wheat straw in percentage by weight was mixed with eucalyptus bark fibres to determine the thermal conductivity of the mixture. The test results are summarized in Table 2.

The introduction of 15 % of chopped wheat straw replacing eucalyptus bark reduces the thermal conductivity coefficient by 6.2–30.2 % depending on the average density of the mixture. The lowest value of the thermal conductivity coefficient, equal to 0.046 W/(m·K), was recorded at densities of 110 kg/m^3 and 200 kg/m^3, which is lower than the index of fine fibres without straw by 11.5 % and 13.3 %, respectively. When increasing the content of straw up to 25 %, the minimum value of the thermal conductivity coefficient was recorded at densities of 180 kg/m^3 and 200 kg/m^3 and was also equal to 0.046 W/(m·K).

The best value of thermal conductivity coefficient of middle fraction fibres was obtained at density of 180 kg/m^3 when adding 15 % of chopped wheat straw. That value is equal to 0.045 W/(m·K), which is 20 % lower than the value of thermal conductivity coefficient of bark fibres without straw. Decrease of the thermal conductivity coefficient relative to the minimum value of bark fibres without straw at densities of 70 and 90 kg/m^3 is 8.2 %. When increasing the percentage of chopped wheat straw up to 25 %, no further decrease in the thermal conductivity coefficient is observed, and the minimum thermal conductivity coefficient increases to 0.047 W/(m·K).

When introducing 15 % of chopped wheat straw into the eucalyptus bark of coarse fraction, changes in the coefficient of thermal conductivity are not noted in comparison with the additive-free composition. Increasing the content of chopped wheat straw in the mixture more than 15 %, leads to crumbling of straw particles at the bottom of the structure-forming mass of fibres and does not allow to obtain a homogeneous mixture.

The thermal conductivity coefficient of the mixture of chopped wheat straw and ultrafine fraction of bark fibres was not studied, because the thermal conductivity coefficient of straw exceeds that of ultrafine fraction of bark fibres.

As a result of tests, it was found that the introduction of chopped wheat straw in the amount of 15 % of the total mixture mass provides a reduction in the thermal conductivity coefficient of the structure-forming mass. However, in contrast to the one-component mixture of bark fibres, a decrease in the fibre cohesion in the two-component mixture is visually noted due to the replacement of part of the fibres with chopped wheat straw.

3.5. Thermal insulation slabs based on eucalyptus bark without binder

After pulping of wood ash in aqueous solution, preparation of structure-forming material from eucalyptus bark and moulding of slabs was carried out according to three variants explained on Section 2.2.

The lowest thermal conductivity coefficient of 0.055 W/(m·K) at a density of 200 kg/m^3 was obtained on slabs moulded from narrow multidirectional strips of bark. The slabs have low rigidity, but at the same time they do not break due to the formed cohesive structure by multidirectional narrow strips of bark.

For the slabs with horizontally laid bark strips at a density of 250 kg/m^3, the thermal conductivity coefficient reached 0.059 W/(m·K). It is noted that the slabs have low cohesion of bark layers with each other, since the bark plates and, respectively, fibres are oriented only in the horizontal dimension within each bark layer.

Also, a similar thermal conductivity, equal to 0.059 W/(m·K), was recorded at a density of 230 kg/m^3 on slabs made of bark fibres crushed by a construction mixer. At the same time, the slabs are rigid and have a cohesive structure.

The obtained experimental samples of slabs confirm the possibility of producing thermal insulation material in the form of slabs without binder by pre-boiling eucalyptus bark in a solution of wood ash. In

Table 2
Thermal conductivity coefficient of a mixture of eucalyptus bark fibres and chopped straw.

Chopped wheat straw content, %	Thermal conductivity coefficient of the mixture, W/(m·K),at an average density, kg/m^3									
	50	70	90	110	120	140	160	180	200	220
Fine fraction of Eucalyptus bark fibres										
0	0.054 *(0.004)*[*]	0.053 *(0.004)*	0.051 *(0.003)*	0.052 *(0.005)*	0.053 *(0.004)*	0.055 *(0.004)*	0.057 *(0.005)*	0.059 *(0.004)*	0.06 *(0.005)*	0.061 *(0.005)*
15	-	0.047 *(0.004)*	0.048 *(0.003)*	0.046 *(0.003)*	0.049 *(0.003)*	0.048 *(0.003)*	0.048 *(0.003)*	0.051 *(0.004)*	0.046 *(0.004)*	0.052 *(0.005)*
25	-	0.050 *(0.004)*	0.048 *(0.004)*	0.051 *(0.003)*	0.048 *(0.004)*	0.052 *(0.004)*	0.047 *(0.003)*	0.046 *(0.003)*	0.046 *(0.003)*	0.051 *(0.003)*
Medium fraction of Eucalyptus bark fibres										
0	0.053 *(0.004)*	0.049 *(0.003)*	0.049 *(0.004)*	0.050 *(0.003)*	0.052 *(0.004)*	0.054 *(0.004)*	0.055 *(0.005)*	0.056 *(0.004)*	0.057 *(0.005)*	0.058 *(0.004)*
15	0.053 *(0.005)*	0.049 *(0.004)*	0.048 *(0.003)*	0.050 *(0.004)*	0.048 *(0.004)*	0.049 *(0.004)*	0.050 *(0.003)*	0.045 *(0.003)*	0.047 *(0.003)*	0.050 *(0.003)*
25	-	0.049 *(0.004)*	0.049 *(0.003)*	0.050 *(0.003)*	0.050 *(0.004)*	0.049 *(0.003)*	0.051 *(0.004)*	0.047 *(0.004)*	0.049 *(0.003)*	0.052 *(0.003)*
Coarse fraction of Eucalyptus bark fibres										
0	0.062 *(0.005)*	0.057 *(0.004)*	0.055 *(0.005)*	0.052 *(0.004)*	0.051 *(0.004)*	0.050 *(0.004)*	0.051 *(0.003)*	0.052 *(0.005)*	0.055 *(0.003)*	0.056 *(0.004)*
15	0.062 *(0.005)*	0.054 *(0.005)*	0.053 *(0.004)*	0.056 *(0.003)*	0.051 *(0.003)*	0.050 *(0.004)*	0.050 *(0.003)*	0.051 *(0.003)*	0.053 *(0.004)*	0.055 *(0.005)*

[*] Numbers between brackets correspond to the standard deviation.

addition, it can be assumed that the slabs of variant 2 and 3 can also be effectively used for sound insulation, as they have a sufficiently high density and fibre structure.

3.6. Effect of binder component on thermal conductivity coefficient of slabs made of eucalyptus bark fibres

Further studies were carried out on medium, fine and ultrafine fractions. The amounts of liquid glass and of bark fibres in the bulk state significantly affect the structure formation and density of samples. Preliminary studies were carried out to select the optimum amount of structure-forming material. They showed that to form a dense structure of slabs with a minimum number of voids, the required average fibre density without binder component is: 250 kg/m^3 for medium and fine fibre fraction and 150 kg/m^3 for ultra-fine fibre fraction. Reducing the average density of the structure-forming material leads to insufficient stiffness of the moulded slabs.

Before introducing the liquid glass, the bark fibres were pre-wetted with water using a sprayer. This is because of the high water absorption of dry bark fibres, causing the liquid glass to not be evenly distributed throughout the entire volume of the structure-forming material when mixing. Water from the liquid glass solution seems to be quickly absorbed into the structure of the bark fibres and the solid phase of liquid glass should remain on the surface of fibres and quickly changes from a viscous state to a friable one. This is probably followed by the rapid formation of a solid amorphous structure, thus losing adhesive properties and the ability to uniformly cover the surface of all bark fibres.

Pre-wetting with water significantly slows down the absorption of water from liquid glass by the porous surface of bark fibres. It was found that the amount of water required for wetting the surface depends on the size of fibres of the structure-forming material. For the moulding of experimental slabs made of medium fraction fibres the water consumption during wetting is reduced by 60 g. This is explained by the fact that the total geometric surface area of medium fibres is smaller than that of fine and ultra-fine fraction fibres.

For moulding slabs of medium and fine fraction of bark fibres water consumption was 480 g, and for ultrafine fraction was 240 g. The amount of dry matter of liquid glass by per sample was 40–80 g. Water consumption was 510–570 g per slab.

The results of studies of sample plates made of a mixture of fibres and liquid glass are presented in Table 3 and Fig. 18 illustrates the results of thermal conductivity coefficient and density graphically. Slabs on ultrafine fraction of bark fibres showed the lowest coefficient of thermal conductivity equal to 0.054 W/(m·K) with the consumption of 40 g of liquid glass (composition 7). Analysing the effect of liquid glass, it was found that the increase in binder consumption from 40 g to 80 g leads to an increase by 14 % on the thermal conductivity coefficient.

The maximum values of thermal conductivity coefficient were obtained on the structure-forming material from the fine fraction of bark fibres. In comparison with 7–9 compositions the thermal conductivity coefficient of slabs on the fine fraction (compositions 4–6) increases on average by 10 %.

In the process of selecting the optimal compositions, not only the thermal conductivity coefficient was considered, but also the condition of the slabs after drying. After the introduction of liquid glass in the amount of 40 g the surface of the slabs flaking of fibres was observed or weakly bonded structure, which does not provide rigidity and geometry of thermal insulation. Rigid slabs without surface flaking were obtained at the consumption of liquid glass in the range of 60–80 g per sample-slab. The slabs of 2 and 8 compositions provide the minimum index of thermal conductivity coefficient 0.059 W/(m·K) (on the medium fraction) and 0.058 W/(m·K) (on the ultrafine fraction), considering the preservation of slab rigidity. The obtained values of thermal conductivity coefficients are lower than the lowest values of the slabs based on the fine fraction (composition 5) by 8–10 %.

3.7. Effect of carbonisation on thermal conductivity coefficient of slabs made of eucalyptus bark fibres

Relatively low coefficients of thermal conductivity of thermal insulation slabs, indicate the need to search for technological solutions to reduce these indicators. One possible option for implementing the task might be the carbonisation of eucalyptus bark fibres, as air permeability increases due to the low particle density [45]. Thermal conductivity can also be reduced through the heat treatment of the material. Sekino and Yamaguchi [46] decreased the thermal conductivity of their insulation panels made from wood shavings by carbonising the material. Although eucalyptus bark does not have an identical structure and composition to wood, similar processes can occur during the carbonisation heat treatment, given their similarities.

Carbonisation was carried out on fibres of ultrafine fraction, which has the smallest thermal conductivity coefficient of the studied fractions. After carbonisation, a 49 % loss in mass and a 50 % decrease in volume of the carbonised fibre mixture obtained from the initial values were observed. At the first stage the thermal conductivity coefficient of carbonised fibres was determined at a density of 80–165 kg/m^3. The thermal conductivity coefficient of carbonised fibres reached 0.036–0.044 W/(m·K), which is 14.3 % lower than that of non-carbonised fibres.

It has been experimentally established that rigid slabs on carbonized fibres at an average density of 269–280 kg/m^3 provide a heat transfer coefficient equal to 0.050–0.054 W/(m·K). During experiments, rigid boards were obtained with the following consumption of components

Table 3
Compositions and properties of slabs from eucalyptus bark fibres on liquid glass.

Nº of composition	Weight of the sample, g	Fraction of the bark fibres, mm	Consumption per sample plate			Density, kg/m^3	Thermal conductivity coefficient, W/(m·K)	Slab condition
			bark fibre, g	liquid glass, g	water, g			
1	520	1.25–2.5	480	40	510	277.3	0.057 *(0.004)**	L
2	540	(medium)	480	60	510	288.0	0.059 *(0.003)*	R
3	560		480	80	510	298.7	0.063 *(0.005)*	R
4	520	0.63–1.25	480	40	570	277.3	0.06 *(0.004)*	L
5	540	(fine)	480	60	570	288.0	0.064 *(0.004)*	R
6	560		480	80	570	298.7	0.068 *(0.005)*	R
7	280	0.16–0.63	240	40	570	149.3	0.054 *(0.003)*	L
8	300	(ultrafine)	240	60	570	160.0	0.058 *(0.004)*	R
9	320		240	80	570	170.7	0.062 *(0.005)*	R

L - Loosely bounded structure
R - Rigid structure
* Numbers between brackets correspond to the standard deviation.

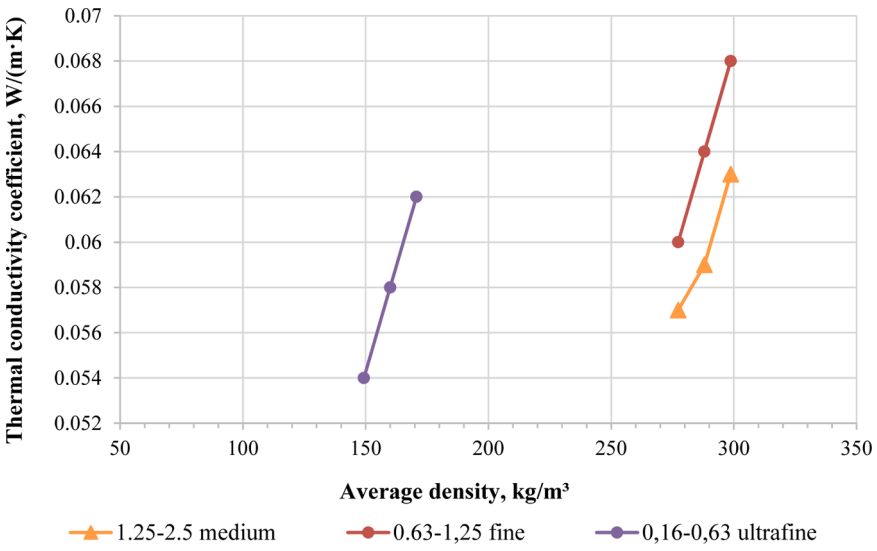

Fig. 18. Thermal conductivity coefficient and density of different fractions of bark fibres and liquid glass.

per sample: 445 g of carbonised bark; 60–80 g by dry matter of liquid glass; 925 g of water.

A large amount of material is required to obtain rigid slabs based on bark fibres, which consequently affects the increase of liquid glass consumption, density and thermal conductivity coefficient. Even though the samples have a rather low thermal conductivity coefficient of 0.050–0.054 W/(m·K), the carbonised fibre slabs should also additionally provide several positive properties. Presumably, in the moisture-saturated state the sorption values of the boards should not reach high values, and carbonised fibres should not rot. The presence of liquid glass will significantly reduce the combustibility of the slabs. Thus, a high durability of carbonised fibre slabs under operating conditions can be assumed.

The ultrafine fraction was chosen because it has the lowest thermal conductivity. When the material is carbonised, all organic substances burn out of the structure and only the carbon porous structure remains, decreasing the coefficient of thermal conductivity. Only one composition was made, using 60–80 g by dry matter of liquid glass, because the liquid glass consumption is already high.

3.8. Sorption moisture content of eucalyptus bark fibres and insulation slabs

Sorption moisture is an important characteristic affecting the performance of thermal insulation under operating conditions. The sorption moisture content was determined on samples taken from the experimental eucalyptus bark slabs after the thermal conductivity coefficient tests.

To determine the sorption moisture content of the samples, the kinetics of the experimental compositions was studied at a relative air humidity of 40–97 %. For this purpose, at certain time intervals the samples were removed from the desiccators and weighed. After determination of sorption moisture content, graphs of kinetics of water vapor sorption by each group of samples were plotted with determination of the final index. Figs. 19–21 show graphs of kinetics of water vapor sorption on the ultrafine fibre fraction as examples.

For non-carbonised and carbonised fibres of 0.16–0.63 mm fraction the sorption kinetics proceeds practically identically with insignificant difference in parameters. Thus, for 3 days at atmospheric humidity of 60 % the sorption of non-carbonised fibres corresponds to 8.9 %, and for carbonised fibres it is 8.1 %. This amounted to 82.8 % and 86.6 % of the maximum sorption moisture equal to 10.8 % and 9.4 %, respectively (Figs. 19, 20). It should be noted that the sorption kinetics at a relative humidity of 40 % is identical to the changes at a relative humidity of 60 %.

At relative humidity of 80 and 90 % for the first 5 days sorption of carbonised fibres coincides and is equal to 13.1 and 13.2 %, respectively, it is 92 and 94 % of the final maximum values. For 5 days sorption

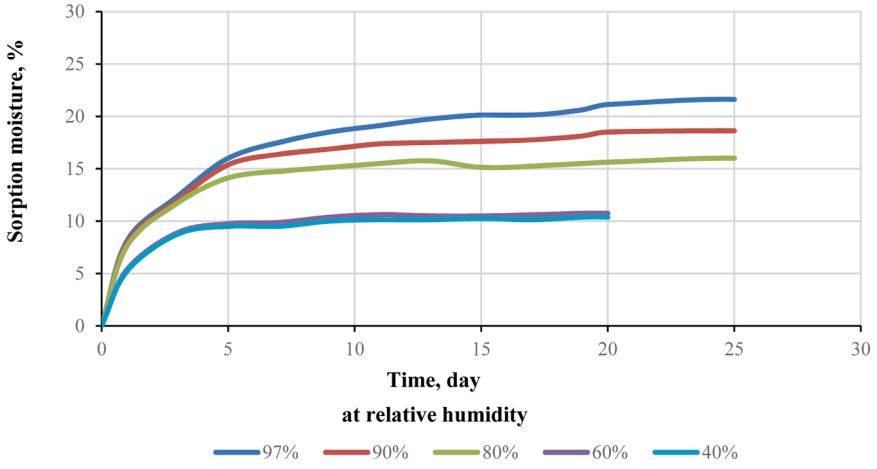

Fig. 19. Kinetics of water vapor sorption made of non-carbonised fibres of ultrafine bark fraction.

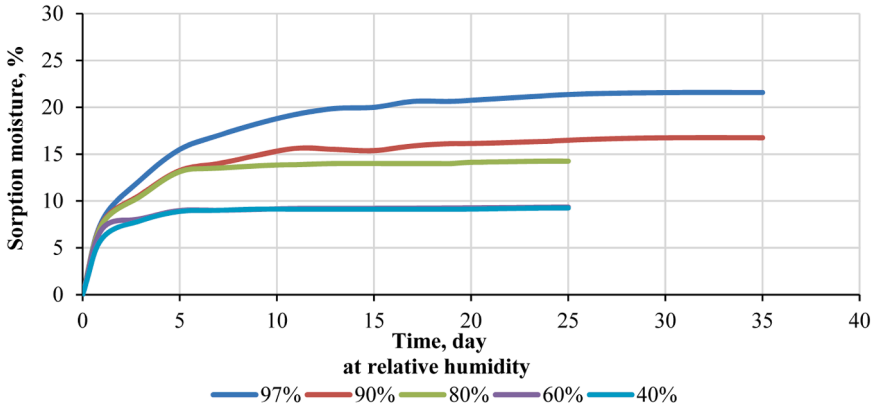

Fig. 20. Kinetics of water vapor sorption by samples made of carbonised fibres of ultrafine bark fraction.

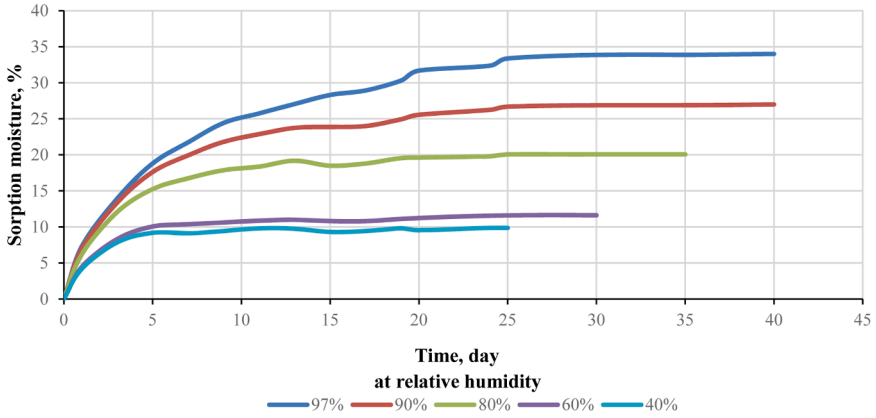

Fig. 21. Kinetics of water vapor sorption of slabs based on carbonised ultrafine bark fibres and liquid glass (60 g).

of non-carbonised fibres, the moisture content is higher by 7.6 % and 16.7 % and reaches 14.1 % and 15.4 %.

The sorption index for the same period at a relative humidity of 97 % for both types of fibres practically does not differ and amounts to 15.5 and 16 %, respectively. Intensive growth of the sorption moisture index of fibres is observed for 15 days. During this period the indices of ultrafine fibres reach 20 % (Figs. 19, 20).

It should be noted that the process of sorption by carbonised fibres is slower. At relative air humidity of 40 % and 60 % sorption of carbonised fibres stabilizes on 25th day, and for non-carbonised fibres the end of the process comes on 20th day. The duration of the sorption process at a relative humidity of 97 % ends only on 35th day (Fig. 20), i.e. 10 days later than for non-carbonised bark fibres.

The introduction of 80 g of liquid glass significantly changed the sorption moisture content and sorption kinetics of the sample plates (Table 4). At a relative humidity of 40 %, the sorption period of non-carbonised fibre samples was 11 days and reached 12.2 %. During the first 3 days, an intensive increase in sorption was observed, reaching

Table 4
Sorption moisture content of experimental compositions.

Composition n°	Composition	Sorption moisture, %, at relative air humidity				
		40 %	60 %	80 %	90 %	97 %
1	Eucalyptus bark fibre fraction 2.5–5 mm (coarse)	6.4 *(0.24)*	10.1 *(0.41)*	14 *(0.59)*	18.5 *(0.85)*	27.5 *(1.2)*
2	Eucalyptus bark fibre fraction 1.25–2.5 mm, (medium)	7.9 *(0.37)*	11.8 *(0.53)*	16.4 *(0.64)*	20.9 *(0.89)*	29.2 *(1.25)*
3	Eucalyptus bark fraction 0.63–1.25 mm, (fine)	7.9 *(0.34)*	12 *(0.49)*	17.1 *(0.81)*	21 *(0.94)*	30.9 *(1.24)*
4	Eucalyptus bark fibre fraction 0.16–0.63 mm, (ultrafine)	10.4 *(0.36)*	10.8 *(0.45)*	16 *(0.71)*	18.6 *(0.89)*	21.6 *(0.93)*
5	Fraction of carbonised eucalyptus bark fibres 0.16–0.63 mm, (ultrafine)	9.3 *(0.41)*	9.4 *(0.38)*	14.3 *(0.65)*	16.8 *(0.75)*	21.6 *(0.89)*
6	Plate of eucalyptus bark fibre 0.16–0.63 mm with 60 g of liquid glass content	11.2 *(0.49)*	13.2 *(0.5)*	19.8 *(0.87)*	24.9 *(1.03)*	32.8 *(1.49)*
7	Plate of eucalyptus bark fibre 0.16–0.63 mm with 80 g of liquid glass content	12.2 *(0.53)*	14.5 *(0.64)*	25.2 *(1.05)*	33 *(1.21)*	38.5 *(1.63)*
8	Plate of carbonised eucalyptus bark fibres 0.16–0.63 mm with 60 g of liquid glass content	9.9 *(0.43)*	11.6 *(0.46)*	20 *(0.94)*	27 *(1.23)*	34 *(1.22)*

*Numbers between brackets correspond to the standard deviation

9.8 %. When introducing liquid glass in the amount of 60 g into samples from carbonised particles, the sorption time increased 2.3 times (25 days), and the index was 9.9 % (Fig. 21), which is 19 % lower than the index of samples from non-carbonised fibres.

The intensity of water vapor sorption by fibres with liquid glass (60 g) for the first 5 days is similar at a relative humidity of 60 %. As a result, the sorption of samples on non-carbonised fibres reached 13.2 % in 25 days, and that of samples on carbonised fibres amounted to 11.6 % in 30 days, which is 12.1 % lower.

The maximum sorption index for non-carbonised fibres with liquid glass (80 g) was 38.5 % at relative humidity of 97 %, and the sorption period was 35 days. At that, intensive increase of sorption moisture index was observed in the first 20 days. The highest sorption of samples on carbonised fibres was 34 % and was achieved after 40 days of testing (Fig. 21).

It is necessary to note the general changes in sorption moisture content for the experimental compositions shown in Table 4. With the decrease in the size of non-carbonised fibres from 5 mm to 0.63 mm (compositions 1–3) there is an increase in sorption moisture content. At relative air humidity of 60 % sorption moisture increases by 18.8 % (from 10.1 % to 12 %). For the 0.63–1.25 mm fraction at relative humidity of 97 % the sorption increase is 12.4 % relative to composition 1 and reaches 30.9 %. When the relative air humidity changes from 40 % to 97 %, the sorption humidity increases 3.7–4.3 times.

It is necessary to note a significant difference in the sorption humidity indicator towards a decrease by 30 % for the fraction 0.16–0.63 mm at relative air humidity of 97 %. This is explained by the formation of dense structure by small fibres which prevents the penetration and slows down the passage of water vapor into the inner area of the samples. With increasing relative air humidity, the sorption index of the 0.16–0.63 mm fraction changes by 2.1 times, which is much less in comparison with the 0.63–5 mm fibre fraction.

With the introduction of liquid glass, a significant increase was recorded in sorption moisture content of samples (compositions 6–8) in comparison with fibre samples without binder (compositions 4, 5). For samples on liquid glass (composition 7) at a relative humidity of 60 % there was an increase in sorption by 34.3 % compared to the index of composition 4, and at a relative humidity of 97 %, respectively, in 1.8 times.

The changes are not so significant on carbonised fibres with liquid glass. At a relative air humidity of 60 %, the sorption moisture content differs insignificantly for compositions 5 and 8. At relative air humidity of 97 % for composition 8 the index increases 1.6 times. The increase of liquid glass consumption from 60 g to 80 g leads to the increase of sorption by 17.4 % at relative air humidity of 97 %.

Earlier experiments on determination of sorption moisture content of sample slabs based on mixtures of vegetable raw materials and liquid glass [40,41,47,48] in comparison indicate rather low indicators of slabs based on eucalyptus bark fibres, which should ensure effective performance of the material under operating conditions. Consequently, it is clear that an increased proportion of sodium silicate in the composition can speed up the water absorption process. This is due to the hygroscopic properties of sodium silicate [49].

After the sorption moisture tests, the samples were left in the bins and not removed from the desiccators to study the resistance to biodegradation by mould fungi. The appearance of mouldy fungi was recorded visually, since the most important factor for thermal insulation is the moment of appearance of mouldy fungi at a certain relative humidity. The appearance of mouldy fungi means the beginning of biodegradation of plant material, which is unacceptable during the operation of insulation materials.

The conducted studies make it possible to clearly determine the environmental conditions (relative humidity) in which it is possible to operate the studied insulation without the risk of mouldy fungi.

The condition of the samples was periodically monitored. On the 80th day of testing, the appearance of mould fungi was recorded on samples made of non-carbonised fibres at 90 and 97 % moisture content.

After 90 days of holding in desiccators, mould fungi were found on the surface of samples made of a mixture of liquid glass and non-carbonised fibres (compositions 6, 7) (Fig. 22).

Compositions 5 and 8, based on carbonised bark fibres, showed resistance to mould growth after 120 days, after which the tests were discontinued.

4. Conclusions

Eucalyptus is a wood species with a wide distribution and growing range. The value of eucalyptus bark as a raw material lies in the fact that the material can come from two independent sources, including wood processing and the natural annual bark shedding of trees. In addition, eucalyptus bark is an environmentally friendly structural material for thermal insulation and is bactericidal and fungicidal, which is particularly important to ensure the durability of plant-based insulation.

Electronic microscopy revealed its porous microstructure, composed of hollow vascular tubes with thin walls and rough surfaces due to microcracks and cellular structures. The grinding process produced fibres of varying thicknesses, enhancing their suitability for insulation. Comparisons with other plant materials confirmed eucalyptus bark's viability as a structure-forming material for thermal insulation.

Pre-wetting of bark before grinding allows to reduce the formation of dust-like particles by 35.4 % and thus reduce the dust mass to 18.1 %. At the same time, the greatest increase in mass by 26.9 % is recorded for ultrafine fraction 0.16–0.63 mm, formed in the amount of 31.6 % of the total mass of ground bark and is the main fraction by mass.

Table 5 summarizes the results obtained for the density and thermal conductivity of the five sample series.

The best thermal conductivity coefficient, equal to 0.042 W/(m·K), was recorded on ultrafine fraction of the eucalyptus bark fibres, with a density of 140–160 kg/m^3.

Mixing chopped wheat straw in the amount of 15 % and 25 % of the mixture mass with fibres of eucalyptus bark provides a decrease in the coefficient of thermal conductivity. For medium and fine fraction of bark this reduction amounted to 8.2 % and 9.8 %, to 0.045 W/(m·K) and 0.046 W/(m·K), respectively, at the density of 110, 180 and 200 kg/m^3.

It is possible to obtain slabs with a relatively low thermal conductivity coefficient. For this purpose, fibre raw material can be cooked in wood ash with further moulding under pressure without binder. The coefficient is 0.059 W/(m·K) at a density of 200–220 kg/m^3, which is 40 % higher than that of ultrafine fibres.

The use of modified liquid glass as a binding component makes it possible to mould rigid slabs on ultrafine and medium fraction of

Fig. 22. Mouldy fungi (white points) on non-carbonised fibres (composition 6).

Table 5
General summary of experimental compositions.

Serie	Method	Density (kg/m^3)	Thermal Conductivity W/(m·K)
First	Ultrafine, fine, medium and coarse fibres without binder	50–220	0.042–0.062
Second	Fractionated fibres of eucalyptus bark and chopped wheat straw (0 %, 15 % and 25 %) without binder	50–220	0.045–0.062
Third	Pulping bark in lye	200–250	0.055–0.059
Fourth	Ultrafine, fine and medium fibres with liquid glass binder	160–298.7	0.054–0.068
Fifth	Ultrafine fraction carbonised with liquid glass binder	269–280	0.050–0.054

eucalyptus bark fibres with thermal conductivity coefficient of 0.058 and 0.059 W/(m·K) at densities of 160 and 288 kg/m^3, respectively.

The use of carbonisation technology allowed to establish that for the fraction of 0.16–0.63 mm at a density of 80–165 kg/m^3 the coefficient of thermal conductivity is in the range of 0.036–0.044 W/(m·K). This is 14.3 % lower than for samples on non-carbonised fibres. The introduction of liquid glass, considering the stiffness of the slabs, causes an increase in the thermal conductivity coefficient by 38.8 % up to the value of 0.05 W/(m·K) at a density of 269 kg/m^3.

With fibre fraction reduction, sorption moisture increases and reaches 30.9 % for the fine fraction at relative air humidity of 97 %. However, for the ultrafine fraction it significantly decreases (by 30 %) to 21.6 %, which is due to the formation of a dense structure by ultrafine fibres even in the bulk state.

Sorption humidity of slabs on liquid glass at relative air humidity of 97 % increases by 2.7 times in comparison with the indicator at relative air humidity of 60 % and reaches the highest value of 38.5 % among the tested samples. For carbonised bark of ultrafine fraction, the limit value of sorption reaches 21.6 %, which is 1.6 times lower than the index of boards with liquid glass. Thus, the presence of liquid glass in compositions with eucalyptus bark fibres leads to an increase in the sorption moisture content of the material.

Thermal insulation materials based on eucalyptus bark fibres, including slabs on non-carbonised fibres, demonstrate high bioresistance to the formation of mould fungi. The appearance of fungi on the samples made of a mixture of non-carbonised fibres and liquid glass at relative humidity of 90 % and 97 % was recorded only on the 90th day. On the surface of non-carbonised bark fibres without binder, fungus was observed after 80 days of testing. Samples containing carbonised fibres had no bio-damage after 120 days of keeping in desiccators at relative humidity of 97 %.

The study demonstrated that eucalyptus bark fibres can be effectively utilised as a structure-forming material for backfill and board insulation, ensuring ecological safety for humans and the environment, as well as resistance to bio-damage. The use of these composite boards can significantly reduce the environmental impacts arising from the construction and agro-forestry sectors. By employing locally sourced waste, it is possible to address challenges related to sustainable resource management and mitigate specific environmental issues. Consequently, this research marks a substantial advancement in promoting sustainable practices within the construction industry and paves the way for practical applications of these materials.

To further enhance the understanding and applicability of eucalyptus bark-based insulation materials, future research should focus on key areas. Fire resistance testing should be conducted to address the combustibility of eucalyptus bark composites, evaluating its safety in construction settings. Full-scale case studies, evaluating the use of these insulation boards in real building environments, can also provide valuable insights into their long-term performance on these insulation boards under varying conditions. Furthermore, conducting a comprehensive environmental impact evaluation through Life Cycle Assessment (LCA) and Life Cycle Cost (LCC) analyses can help quantify both the ecological and economic advantages, reinforcing the potential of these materials as sustainable, cost-effective solutions for the construction industry.

CRediT authorship contribution statement

Nadezhda Bakatovich: Writing – original draft, Validation, Methodology, Investigation, Formal analysis. **Aliaksandr Bakatovich:** Writing – original draft, Validation, Supervision, Methodology, Conceptualization. **Florindo Gaspar:** Writing – review & editing, Validation, Conceptualization. **Alana Silva:** Writing – review & editing, Methodology, Formal analysis.

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.

Data availability

The authors do not have permission to share data.

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