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ESTABLISHING PATTERNS IN THE FORMATION OF BIOCOMPOSITES FOR THERMAL INSULATION OF BUILDING STRUCTURES

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This study's object is the process that forms fire-resistant biocomposites based on wood chips and inorganic and organic binders. The task addressed relates to the need to enable resistance to high-temperature flames. This is important for the technology of application and production of environmentally friendly biocomposites obtained from natural and renewable sources for construction.

It has been proven that when determining the thermal insulation properties of the resulting materials, the temperature conductivity of the biocomposite on an inorganic basis was $0.22 \cdot 10^6$ m^2/s while the thermal conductivity of the sample did not exceed 0.132 W/(m·K). In contrast, for an organic-based biocomposite, the thermal conductivity value decreases by more than 6 times, the temperature conductivity – by more than 7 times.

In addition, the heat capacity of the product based on inorganic binder corresponds to a value within 1.6 kJ/(kg·K), and the heat capacity value for the product made of biocomposite based on organic basis was 7.66 kJ/(kg·K), respectively.

When a radiation panel was applied to the biocomposite samples, the temperature of the gaseous combustion products increased to 96°C, and the sample did not ignite. A study of the compressive strength of biocomposites showed that the product formed on the basis of wood and inorganic binder is more fragile; the tensile strength corresponds to an average value of 0.5 MPa. In contrast, for the biocomposite formed on the basis of chips and organic binder, the average tensile strength is 2.4 MPa, which is more than 4.7 times higher than the product based on inorganic basis.

The practical importance relates to the fact that the results were taken into account when developing a thermal insulation product for construction. Thus, there are grounds for the production of biocomposites for thermal insulation

Keywords: biocomposites, thermal insulation products, thermophysical properties, fire resistance, foam coke layer, coating swelling

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1. Introduction

The development of highly efficient biocomposites made from natural resources such as wood is growing worldwide, as it is an environmentally friendly material and has a number of positive properties. These include low density, thermal conductivity, and a certain hardness, which allows them to be successfully used in construction. However, they are subject to fire, which limits their scope and requires fire protection. A small number of preparations have been proposed for the comprehensive protection of wood from fire, in particular mixtures of flame retardants such as ammonium sulfate and diammonium phosphate, sodium orthoborate and boric acid, and a mixture of sodium carbonate and boric acid. However, this requires an assessment of the process of fire resistance of biocomposites used for construction, since increasing the fire-resistant properties of biocomposites using flame retardants can reduce their mechanical strength.

The simplest high-temperature and fire-retardant agents based on inorganic binders contain bound water, which evaporates during heating and blocks the transfer of heat to the protected surface. Sodium liquid glass, Portland cement, alumina cement, phosphate, and aluminosilicate binders are used as binders for such materials. However, such coatings are short-lived and ineffective since they do not provide sufficient adhesion strength. The effectiveness of the use of fire-retardant coatings based on organic substances has been attributed to the action of flame retardants and foaming agents; it is possible to significantly influence the formation of a foam coke layer, as well as to increase the stability, density, and strength of the coke layer through the directional formation of polymer additives.

The formation of fire-resistant biocomposites is associated with a high risk of surface defects, which level the result obtained and require research to determine the compatibility of the binder and wood and the resistance of the coating to operating conditions because under conditions of temperature and humidity fluctuations, individual coatings dissolve in water and degrade from the surface of the wood. In addition, it is necessary to emphasize compliance with the technological regime and proper preparation for use.

Thus, studies aimed at establishing the effectiveness of the formation of a fire-resistant coating and changes in its structure during operation, which are necessary to determine the parameters of fire resistance, are relevant.

2. Literature review and problem statement

Paper [1] reports that fire-resistant composites have been studied for over four decades and the demand for this type of product in various applications is constantly increasing. As biocomposites have become popular nowadays, researchers have turned their attention to the production of fire-resistant biocomposites. The main advantage of a biocomposite is its easy degradation process by natural biocomposites. These types of composites can be partially biodegradable or fully biodegradable, and the degradation rate depends on the material content. Partially biodegradable ones usually contain natural fiber as a reinforcing material, as well as a non-biodegradable synthetic resin, while fully biodegradable ones contain either only biopolymers or a mixture of natural fiber and biopolymer. Typically, fire-resistant biocomposites also contain an additional fire-resistant filler. The cited paper reviews the research conducted on the development of flame-retardant biocomposites and attempts to point out the key factors that can control the properties of the final product. This is necessary so that further research can produce products with the desired properties. However, no optimal solutions for use have been identified.

In [2], the study focused on the thermal characterization of a recently developed green biocomposite to assess thermal stability, identify gaseous emissions, and calculate the lower flammability limit (LFL). An intumescent flame-retardant coating consisting of ammonium polyphosphate-tris(2-hydroxyethyl)isocyanurate (APP-THEIC) and boric acid (BA) was applied to a composite consisting of 38% bio epoxy resin and flax fiber to improve the thermal profile of the material. The hazards of new materials for emergency response were identified using NFPA 704. In the study, the developed GBC was characterized based on its thermal decomposition profile, degradation temperature, gaseous emissions, and lower flammability limit. It was observed from the TG curves that the green biocomposite completely decomposed at approximately 600°C. The application of an intumescent flame retardant (IFR) coating improves the fire resistance of the material, and the final degradation temperature of the material reaches approximately 800°C. A QSPR study of the gaseous emissions generated from the pyrolysis of the green biocomposite shows that the LFL decreases with increasing temperature up to 750°C. However, from the toxicity analysis of the gaseous emissions during degradation, the biocomposite releases a large amount of phenol above 350°C, which is hazardous to health when inhaled.

In paper [3], flammability tests and detailed studies of the properties of polymer composites containing lignin are described. The composites were obtained using bisphenol A glycerolate diacrylate (1 glycerol/phenol) (BPA.GDA), ethylene glycol dimethacrylate (EGDMA) and kraft lignin (lignin alkali, L) during UV curing. After modification with phosphoric acid (V), lignin, as well as diethyl vinyl phosphonate, were used as flame retardant additives. The changes in the chemical structure (ATR-FTIR) and the effect of different additives on hardness, thermal (TG) and mechanical properties were discussed in detail. The samples after flammability tests were also examined to assess their thermal degradation. However, it is not stated how the flame retardant affects the flame mitigation.

In [4], it is noted that biocomposites are usually formed by binding natural fibers derived from plants or cellulose with organic binders. One such material is sawdust, and varieties of composite boards are manufactured using sawdust as a filler. Both the matrix and the sawdust are flammable, so the use of an inorganic matrix is considered to improve fire resistance. The inorganic matrix can withstand temperatures up to 1000°C and provides protection against sawdust for a short period of time. The strength of these boards was increased by reinforcing with a very low percentage of high-strength glass fibers and carbon fibers. Samples were manufactured using different proportions of sawdust from 11% to 38% by weight and were tested in compression and bending to obtain the main mechanical properties and determine the optimal sawdust content. The results show that it is possible to manufacture these types of composite beams to achieve the desired strength without the use of special equipment. But it is not indicated how the coating is operated.

Renewable and biodegradable polylactide (PLA), as noted in [5], has excellent mechanical strength but is flammable, which limits its practical application. Many phosphorus/nitrogen (P/N)-based flame retardants are effective in PLA, but their high addition usually reduces the mechanical strength of the PLA bulk. Regarding polyphosphoramides, despite their high flame retardant efficiency, their chemical synthesis often generates chemical waste as by-products. Using only 3 wt.% APN, the resulting PLA exhibits desirable flame resistance, including a UL-94 V-0 rating and a limiting oxygen index of 37.6%. In addition, the viscosity of the flame retardant PLA increases by 85% compared to pure PLA, while maintaining both tensile strength and thermal stability. However, their impact on the ecosystem is not detailed.

In [6], it was shown that the mechanical properties of flame-retardant biocomposites are significantly degraded due to the large amount of flame retardants (FRs) required for satisfactory results and the limited interfacial interaction between the FRs and polymer/natural fibers. The study addresses these issues by modifying the vacuum resin injection molding (VARTM) process to include two inlets and two outlet ports. This allows for the simultaneous injection of the FR-filled resin into the top layer and the pure resin into the other layers. The clay mineral vermiculite (VCM) was used as a FR additive in vinyl ester (VE) using mechanical mixing methods such as a three-roll mill and overhead mixing. Bamboo fabric (BF) was used as a reinforcing material in the fabrication of flame-retardant VC-VE/BF biocomposites. The VO-filled side demonstrated excellent fire resistance (with a peak heat release rate (pHRR) of 467.1 W/g) and a 44% increase in thermal stability compared to the rest of the composite. However, the environmental impact is not noted.

Recently, researchers [7] have made significant efforts to find biodegradable and environmentally friendly reinforcing materials for the production of composite-based products. After their use, there is a problem of disposing of these materials, which leads to various environmental hazards such as pollution and landfills. Therefore, the evaluation of the biodegradability of green composites is also important, which is mostly carried out by microorganisms. Therefore, it can be concluded that understanding the flammability and degradation of biocomposites along with their testing methods is important for the development of biocomposites with better fire resistance, thermal decomposition, and biodegradability characteristics. The cited review focuses on fire resistance, thermal stability, and degradation of polymer composites based on natural plant fibers during and after their service life. However, it is not noted how their properties change during operation.

Biocomposites reinforced with natural fibers, as presented in [8], are an environmentally friendly and inexpensive alternative to traditional petroleum-based materials and are used in a wide range of industrial applications due to their numerous advantages. In particular, such as good mechanical properties, low production costs, renewability, and biodegradability. Additives known as flame retardants (FRs) are widely used to improve the fire resistance of wood and biocomposites, textiles, as well as in other industries, in order to expand their applications. This practice is currently very common in the construction sector due to strict fire safety regulations for residential and public buildings. To create a holistic picture, the flammability of wood and natural fibers as material resources for the production of biocomposites was investigated. In addition, the potential of lignin as an environmentally friendly and inexpensive fire-resistant additive for the production of high-performance biocomposites with improved technological and fire-resistant properties was discussed in detail. But it is not noted what makes it a good thermal insulator and thermal stability.

The design of biodegradable polymers is increasingly developing through various combinations with other materials [9]. There are great expectations regarding how the use of these new materials can be expanded not only as a replacement for fossil polymers but also as a replacement for metallic materials. The cited paper reports the use of numerical modeling as a tool to evaluate and reengineer the application of a biodegradable composite consisting of nano fibrillated cellulose (NFC) and poly(lactic acid) (PLA) in the production of mechanical components. Academic and industrial interest in this work led to a case study using the finite element method (FEA) and the resulting composites, where the technical feasibility of replacing a mechanical component made of 1060 H12 aluminum alloy was evaluated. However, a key role in their resistance under severe fire exposure was not noted.

In study [10], three bio aggregates were analyzed for their potential use in the production of biocomposites with potato starch binder. Technologically important properties, such as particle size, shape, and bulk density in compacted form, as well as the properties of the resulting biocomposites, were determined. The main characteristics of the aggregates are relatively similar: density 80–100 kg/m^3, thermal conductivity 0.042–0.045 W/m·K, specific heat capacity 1240–1330 J/g·K, kinetic water absorption from 456 to 584%. This leads to similar basic properties of the resulting biocomposites: density of about 200 kg/m^3, thermal conductivity of 0.053–0.062 W/m·K, specific heat capacity of 1250–1450 J/kg·K, with a difference in compressive strength of 0.2 to 0.8 MPa. The created starch binders and fillers from agricultural by-products can be used in the production of boards where strength is required, for example, windbreak boards, as well as thermal insulation boards under the floor. However, these products cover a small range of applications.

The gradual development of public policies for ecological transition in the modern construction sector, as reported in [11], encourages researchers to investigate new alternative and environmentally friendly materials, with a special focus on biomaterials. From this perspective, the mechanical, thermal insulation, and sound absorption characteristics of a waste coffee grounds/potato starch biocomposite were analyzed for potential applications in buildings. Based on thermal conductivity and diffusion coefficient tests, the waste coffee grounds biocomposite was characterized as an insulating material comparable to conventional plant-based thermal insulation materials. Acoustic tests revealed absorption coefficients in the same range as other conventional materials used to enable acoustic comfort in buildings. This biomaterial demonstrated sufficient mechanical compressive strength for non-load-bearing structures and sufficient mechanical strength for molding into building bricks. It is not established how the mechanical and thermal characteristics change with the humidity of the environment.

In paper [12], the advantages, disadvantages, and problems that still remain unclear regarding the success of creating biocomposite materials of the HEMPCRETE type are described. The most important aspect emphasized in the literature on the creation and use of this type of material is the extremely low impact of CO_2 pollution, which usually accompanies the technological processes of production, implementation, and operation of building materials. This technology contributes to environmental protection and pollution reduction, energy saving and ensuring a hygienic and healthy living climate. The results indicated the valuable properties of this material (light, permeable, which contributes to thermal insulation) and its sensitive points (high water absorption, which requires the need for surface protection, mechanical strength, which requires careful consideration of the choice of safety conditions of use). However, nothing is said about the environmental friendliness of these products.

The study reported in [13] describes the production and characterization of thermally stable, mechanically stable composite foams based on cellulose fiber (CF) reinforced with alumina nanofibers (ANF). To evaluate the effect of ACF on rheology and drainage, CF suspensions were prepared at a concentration of 20 g/kg, with the addition of 2%

and 5% ACF. Mechanical and thermal analyses of dried CF with 2% ACF revealed a significant improvement in strength and thermal stability. The incorporation of ACF into CF foams improves their rheological properties, mechanical and thermal characteristics, and reduces the burning rate.

Work [14] outlines the basics of aerogel production as the lightest solid material in the world and its undeniable importance for a wide range of applications, such as thermal and acoustic insulation, environmental protection, biomedical applications, and energy storage. It presents numerous ways to combine lignin and aerogel, emphasizing the importance of synergistic improvement of pore structure, surface area, mechanical reinforcement, and thermal stability of aerogels.

The study reported in [15] aimed to design and optimize environmentally friendly biocomposite ceiling tiles by partially replacing gypsum with pearl millet waste combined with wheat flour waste (WWF) and wastepaper. The optimized composition for minimum thermal conductivity (0.065 W/m·K) was determined as 45% PMSC and 10% gypsum at 12 mm thickness. For maximum flexural strength (1.24 MPa), the optimal mixture was 55% PMSC and 30% gypsum at 14 mm thickness. These results emphasize the critical influence of gypsum and tile thickness on improving the performance of the material. The built regression models have demonstrated predictive value for thermal conductivity and flexural strength, as well as an error below 3%, confirming the reliability of the approach.

Our review of the literature [3–6, 8–10] has found that thermal insulation biocomposites are able to increase resistance to fire during operation but the parameters that enable their resistance to thermal effects have not been determined. Therefore, establishing the parameters of the formation of biocomposites and the influence of the components that make up their composition, as well as their role in ensuring fire resistance, necessitates research in this area.

3. The aim and objectives of the study

The purpose of our work is to identify the regularities in designing fire-resistant biocomposites for thermal insulation of buildings. They could make it possible to expand the scope of use of biocomposites in the construction of buildings.

To achieve the goal, the following tasks were solved:

– to investigate the thermophysical properties of biocomposites based on wood sawdust and inorganic and organic binders;

– to determine the features of combustion of biocomposites under thermal action and the influence of fire protection on combustion suppression;

– to establish the strength characteristics of biocomposites based on wood sawdust and inorganic and organic binders.

4. The study materials and methods

4. 1. The object and hypothesis of the study

The object of our study is the process that forms fire-resistant biocomposites based on wood chips and inorganic and organic binders. The scientific hypothesis assumes stability of the biocomposite during interaction with a high-temperature flame and the establishment of thermal insulation properties when the temperature changes.

During our study, it was assumed that progress in the process of forming biocomposites is constant under the influence of external conditions. It was simplified that the temperature, humidity, as well as pressure of wood processing, do not change.

4. 2. The studied materials used in the experiment

Samples of a biocomposite based on wood chips and a binder were prepared by molding in a plastic mold measuring 300 × 140 × 50 mm. The filler for the plates was wood chips previously produced from sawmill production dried to a moisture content of 10%. A cement-sand mortar diluted with water and liquid glass in a ratio of 1:1 and an organic-based binder coating "SKELA-W" were used as a binder.

The wood chips and the binder were placed in a container and mixed. Mixing was carried out until the chips were completely wet, after which the prepared raw material mixture was placed in a mold. After filling the mold, the samples were kept for 14 days at room temperature and a relative humidity of about 65%.

The biocomposite was prepared with the following ratios of mass parts of the filler and binder 1:1 (Fig. 1):

1) wood chips – inorganic-based binder;

2) wood chips – organic-based binder.

a

b

Fig. 1. Model samples of biocomposite:
a — based on wood chips — inorganic binder;
b — based on wood chips — organic binder

After the plates were manufactured, samples were obtained from them for testing. Thus, the dimensions and density of the samples for different binder variants were:

– for inorganic binder – 300 × 140 × 32 mm, density 447 kg/m^3;

– for organic binder "SKELA-W" – 300 × 140 × 38 mm, density 148 kg/m^3.

4. 3. Methodology for determining fire resistance indicators of biocomposites

The study of the thermal insulation properties of biocomposites was carried out according to the methodology given in [16]. The essence of the studies on determining thermal conductivity is that a heater with a thermocouple was placed on the material sample, and a control thermocouple was placed on the reverse wall of the sample. At the same time, the end of the thermocouple was fixed so that the sample was pressed against it. The voltage was turned on the heater and the temperature on the sample surface was measured. The criterion for determining the thermal conductivity of the material under thermal action is the time of reaching the maximum temperature value ($0.5 \cdot T_{max}$) on the reverse surface of the sample. The thermal insulation properties of the sample were calculated from the measured values.

Studies to determine the thermal stability of fire-resistant insulation were carried out using a methodology that involved exposing the sample to a radiation panel and igniting it, measuring the temperature of combustion products and the time it was reached, the time of ignition and passage of the flame front through the surface areas, and the length of the burned part of the sample. The flammability index was calculated using data [17].

To establish the operational properties of the biocomposite, the compressive strength was determined according to ISO 13061-3:2014 [18].

5. Results of determining the properties of the biocomposite during operation

5. 1. Experimental studies of the thermal conductivity process of biocomposites and their results

To establish the thermophysical characteristics of biocomposites, studies were conducted on their thermal conductivity under the action of a heating device (Fig. 2). The heater had the following characteristics: a nichrome wire with a resistance of 84 Ohms was wound on an electrically insulating plate measuring 100 × 100 mm and a thickness of 1 mm, to which a voltage of 14.5 V was applied. The heater was placed in a thermal insulating plate to reduce heat loss along the perimeter.

The results of our studies on determining the temperature and duration of the induction time of heat transfer through the sample, performed according to the methodology and equipment given above, are shown in Fig. 3.

When using a biocomposite on an inorganic binder (Fig. 2), the heat transfer process increases to 1200 s and over 1550 s for a sample on an organic binder. It was found that when using a sawdust product based on an organic binder as thermal insulation, the thermal conductivity of this sample is characterized by a very long heat transfer time. Namely, the heat transfer process is inhibited by the formed air barriers in the material, which makes it possible to influence the thermal insulation process.

Based on the results of the measured temperature, the thermophysical characteristics of the biocomposites were calculated, which are given in Table 1.

a

b

Fig. 2. The process of determining the thermal conductivity of a biocomposite sample under the action of a heater: *a* – inorganic-based sample; *b* – organic-based sample

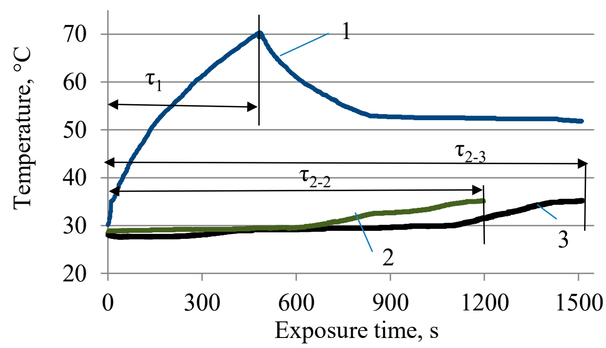

Fig. 3. Results of thermal conductivity tests of the biocomposite: 1 – heating curve; 2 – temperature values on the inverted surface for a product based on chips and inorganic binder; 3 – temperature values on the inverted surface for a product based on chips and organic binder. Points τ_1 correspond to the average temperature value of the heating curve; τ_2 – the average temperature value on the inverted surface

Table 1

Thermophysical characteristics of a thermal insulation product

Biocomposite	Thickness, mm	Weight, kg	Estimated product characteristics					
			Density ρ, kg/m^3	Thermal activity, W·s$^{1/2}$/(m^2·K)	Temperature conductivity, m^2/s	Thermal conductivity λ, W/(m·K)	Heat capacity, kJ/(kg·K)
On inorganic binder	32.0	0.60	447	306	$0.22 \cdot 10^{-6}$	0.132	1.6
On organic binder	38.0	0.24	148	328	$0.03 \cdot 10^{-6}$	0.021	7.66

When determining the thermal insulation properties of materials, it was found that the thermal conductivity of the thermal insulation product made of an inorganic-based biocomposite was $0.22 \cdot 10^{-6}$ m^2/s, the thermal conductivity of the sample did not exceed 0.132 W/(m·K). However, for an organic-basedbiocomposite, compared to a cement-based biocomposite, due to the formed air pores, the thermal conductivity value decreases by more than 6 times, and the thermal conductivity by more than 7 times. In addition, the heat capacity of the product on an inorganic binder corresponds to a value within 1.6 kJ/(kg·K), and the heat capacity value for the product made of an organic-based biocomposite was 7.66 kJ/(kg·K), respectively. Thus, these products correspond to the values of the thermal insulation material, since the values of thermal diffusivity, thermal conductivity, and heat capacity given above are compared with the main thermal insulation building materials given in DBN V.2.6-31:2021. Constructions of buildings and structures. Thermal insulation of buildings. Thus, polystyrene foam boards have a thermal conductivity of 0.034 W/(m·K) and a heat capacity of 1.34 kJ/(kg·K).

Table 2

The time it took for the flame front to pass control points

Sample of a biocomposite based on wood chips and:	Flue gas temperature, °C		Ignition time, s	Time of passage of the flame front through the sample sections, s									Time to reach maximum flue gas temperature, s	Burning length of the sample, mm	Flammability index
	T_1	T_{max}		1	2	3	4	5	6	7	8	9			
Inorganic binder	57	83	–	–	–	–	–	–	–	–	–	–	600	0	0
Organic binder	69	96	–	–	–	–	–	–	–	–	–	–	600	0	0

Fig. 4. Test results of the ignition process and flame propagation of an inorganic-based biocomposite: *a* – test sample; *b* – burning of the sample

Fig. 5. Results of testing the ignition process and flame propagation by an organic-based biocomposite: *a* – test sample; *b* – thermal effect on the sample; *c* – sample swelling

5. 2. Results of determining the thermal stability of biocomposites under the action of high-temperature flame

Fig. 4–6 and Table 2 illustrate the process of ignition and flame propagation by a biocomposite.

The results of our studies on determining the increase in the maximum temperature of gaseous combustion products (*Dt*, °C) of wood material, conducted under laboratory conditions, are shown in Fig. 6, Table 2.

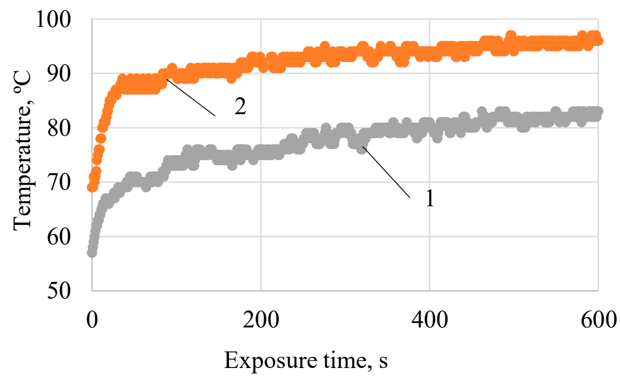

Fig. 6. Dynamics of flue gas temperature increase during biocomposite tests: 1 – based on inorganic binder; 2 – based on organic binder

Studies have shown (Fig. 5, 6) that biocomposites are flame retardant materials since no smoldering was recorded during thermal exposure, and the temperature did not exceed 100°C.

When the radiation panel was applied to samples of biocomposites formed on an inorganic binder (curve 1, Fig. 6), the temperature of the gaseous combustion products increased to 83°C, and the sample did not ignite. During the thermal action on a sample of a biocomposite formed on an organic binder, it did not ignite, the maximum temperature of the flue gases was about 96°C, and the flammability index was 0 (Table 2). This is explained by the fact that when using an inorganic binder, a non-combustible structure is formed on the surface of the wood, which prevents combustion. In contrast, the formation of a heat-insulating layer of foam coke under the influence of thermal influence is characteristic of an organic binder, which slows down the passage of temperature.

5. 3. Results of determining the strength characteristics of biocomposites

In order to determine the operational properties of biocomposites in the construction of thermal insulation of building structures, a strength determination was carried out. Fig. 7, Table 3 give the results of our studies on the resistance of the obtained biocomposites to compression.

Our study on the compressive strength of biocomposites showed that the product formed on the basis of wood chips and an inorganic binder is more brittle, so the tensile strength corresponds to an average value of 0.5 MPa. In contrast, for a biocomposite formed on the basis of chips and an organic binder, the average tensile strength is 2.4 MPa, which is more than 4.7 times greater than that of a product on an inorganic basis. Accordingly, the compressive deformation for a biocomposite based on an organic binder exceeds the value for a product on an inorganic basis by more than three times.

Fig. 7. Determining the compressive strength of biocomposites

Table 3

Compressive strength of biocomposite samples

Sample	Dimensions, mm		Load max, P, N	σ, MPa	Deformation, mm
	b	h			
Biocomposite based on chips and organic binder					
1	22.02	25.22	1263.88	2.29	11.59
2	25.14	25.29	2035.29	3.21	12.21
3	25.66	23.41	1184.39	2.02	11.68
4	25.61	25.02	1560.91	2.42	11.51
5	24.17	26.11	1326.89	2.09	11.69
Biocomposite based on chips and inorganic binder					
6	28.01	19.71	201.77	0.39	2.69
7	24.44	18.14	309.40	0.68	2.41
8	25.76	17.46	140.01	0.31	4.21
9	24.51	18.81	250.45	0.49	1.82
10	26.01	20.91	370.36	0.69	2.81

6. Discussion of results related to the study on the regularities of the formation of fire-resistant biocomposites

When studying the process of heat transfer through the thermal insulation layer of the biocomposite, as follows from our results (Table 1, Fig. 2, 3), it is natural that the process of heat transfer increases to 1200 s and over 1550 s for the sample on an organic binder. It was established that when using a product made of sawdust based on an organic binder as thermal insulation, the thermal conductivity of this sample shows that it is characterized by a very long heat transfer time. Namely, the heat transfer process is inhibited by the formed air barriers in the material, which makes it possible to influence the thermal insulation process. This dependence on the density of the material, type, size, location of air cells, etc., slows down the heat transfer processes.

According to the results of our research, it was found that during the tests, the thermal conductivity of the thermal insulation product made of an inorganic-based biocomposite was $0.22 \cdot 10^{-6}$ m^2/s, the thermal conductivity of the sample did not exceed 0.132 W/(m·K). In contrast, for an organic-based biocomposite, due to the formed air pores, the thermal conductivity value decreases by more than 6 times, the thermal conductivity by more than 7 times, and the heat capacity increases by 4 times. In addition, the heat capacity of the product on an inorganic binder corresponds to a value within 1.6 kJ/(kg·K), and the heat capacity value for the product made of an organic-based biocomposite was 7.66 kJ/(kg·K), respectively. This confirms that the above biocomposites can be effectively used as thermal insulation products and provide inhibition of thermal destruction of wood [19, 20].

As we can see from Fig. 4–6 and Table 2, when the radiation panel was applied to samples of biocomposites formed on an inorganic binder, the temperature of gaseous combustion products increased to 83°C, the sample did not ignite. During the tests of the sample of biocomposite formed on an organic binder, it did not lead to ignition, the maximum temperature of flue gases was about 96°C, and the flammability index was 0. This shows that when using an inorganic binder, a non-combustible structure is formed on the surface of the wood, which prevents combustion. In contrast, the organic binder is characterized by the formation under the influence of thermal influence of a heat-insulating layer of foam coke, which slows down the passage of temperature. That, in turn, confirms the mechanism of operation of the fire-retardant coating, which makes it possible to identify it by high-temperature exposure [21, 22].

Unlike the studies reported in [2, 5, 7], in which attention was paid to the use of reinforcing products, our study has considered the formation of biocomposites based on organic coatings, which is quite well known on the market.

However, in contrast to the results from [2] regarding the mechanism of fire resistance, the following can be stated:

– the main necessity of slowing down the thermal effect on wood inherent in inorganic coatings is the release of water vapor, which affects the flame and the formation of a ceramic phase;

– the mechanism of operation of the fire-retardant coating is that under the influence of thermal action, the decomposition of flame retardants begins under the influence of temperature with the absorption of heat and the release of non-combustible gases and the formation of a heat-protective coke layer on the surface of the wood.

Interpretation of our results regarding the fire resistance of biocomposites confirms the effectiveness of the reaction to thermal action and reveals the possibilities of their exploitation. The results of the experiments allow us to state the establishment of a mechanism for using biocomposites for thermal insulation, which are certain advantages of this study.

The results regarding the compressive strength of biocomposites have certain limitations since the product formed on the basis of wood chips and an inorganic binder is fragile and requires an increase in the inorganic binder and subsequent consideration of thermal insulation properties.

In addition, the resistance of the biocomposite to thermal effects provides insufficient information due to the scarcity of data and limits the use of our results. The disadvantages of the study include the fact that the results of the experiments, having the most complete description of the features of thermal insulation properties, are a graphical form of display. However, as a result of experimental studies, a path has been obtained that allows us to establish the role of the intumescent coating in fire resistance.

Further studies on the formation of biocomposites for building structures should, in particular, optimize experimental data on the development of the formulation.

7. Conclusions

1. When using a biocomposite on an inorganic binder, the heat transfer process exceeds the exposure time of 1200 seconds and more than 1550 seconds for a sample on an organic binder. When determining the thermal insulation properties of materials, it was found that the thermal conductivity of a heat-insulating product made of a biocomposite on an inorganic basis was $0.22 \cdot 10^{-6}$ m^2/s, the thermal conductivity of the sample did not exceed 0.132 W/(m·K). In contrast, for a biocomposite on an organic basis, due to the formed air pores, the thermal conductivity value decreases by more than 6 times, the thermal conductivity by more than 7 times, and the heat capacity increases by 4 times. In addition, the heat capacity of the product on an inorganic binder corresponds to a value within 1.6 kJ/(kg·K), and the heat capacity value for a product made of a biocomposite on an organic basis was 7.66 kJ/(kg·K).

2. When a radiation panel was applied to samples of biocomposites formed on an inorganic binder, the temperature of the gaseous combustion products increased to 83°C, and the sample did not ignite. During testing, a sample of a biocomposite formed on an organic binder did not ignite, the maximum temperature of the flue gases was about 96°C, and the flammability index was 0. This is explained by the fact that when using an inorganic binder, a non-combustible structure is formed on the surface of the wood, which prevents combustion. In contrast, an organic binder is characterized by the formation of a thermally insulating layer of foam coke, which slows down the passage of temperature.

3. Our study on the compressive strength of biocomposites has demonstrated that the product formed on the basis of wood chips and an inorganic binder is more brittle, so the tensile strength corresponds to an average value of 0.5 MPa. In contrast, for a biocomposite formed on the basis of chips and an organic binder, the average tensile strength is 2.4 MPa, which is more than 4.7 times greater than that of a product on an inorganic basis. Accordingly, the compressive deformation for a biocomposite based on an organic binder exceeds the value for a product on an inorganic basis by more than three times.

Conflicts of interest

The authors declare that they have no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study, as well as the results reported in this paper.

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Data availability

All data are available, either in numerical or graphical form, in the main text of the manuscript.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

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