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ESTABLISHING THE RULES OF FORMATION OF FIRE-RESISTANT BIOCOMPOSITES FOR BUILDING MATERIALS

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The object of this study is the process of forming a heat-insulating layer of foam coke under thermal action on a biocomposite with the presence of an intumescent coating. The task addressed is to establish the effectiveness of the formation of a heat-insulating intumescent layer of foam coke under thermal action on an intumescent coating, which effectively inhibits high temperature. It has been proven that when wood and fabric are treated with fire retardants, chemical bonds arise that characterize symmetric and asymmetric valence vibrations of C–H in the methyl and methylene groups of lignin and cellulose. For wood treated with an intumescent coating, the value of the adhesive strength was set at 0.25 MPa, while the destruction occurred along the polymer shell with a detachment area of about 25 %. For particleboard treated with an intumescent coating, the value of the adhesion strength is about 0.45 MPa, while the failure occurred along the polymer shell with a separation area of about 10 %.

Based on the results, it was found that under the action of the burner flame, the temperature of the gaseous combustion products did not exceed 185 °C, and the mass loss was less than 2 %. During the thermal action of the coating, a layer of foam coke more than 20 mm thick was formed. Under the action of the burner flame on the biocomposite based on tarpaulin fabric, intensive swelling of the coating began, which led to the formation of a heat-insulating layer of foam coke more than 9 mm thick, ignition and flame spread did not occur.

Thus, the mechanism of fire protection by an intumescent coating is determined by decomposition under the influence of temperature with heat absorption and release of non-combustible gases; by inhibiting oxidation in the gas and condensed phases and by forming a heat-protective coke layer on the surface of the material.

The practical significance of the study is that the results related to determining the flame retardant properties of biocomposites could be taken into account when designing fire-resistant structures

Keywords: biocomposites, fire resistance, intumescent coating, plant materials, adhesive ability, foam coke layer

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1. Introduction

Wood is one of the most common structural materials in construction. However, during its processing and construction of structures, a significant amount of waste is generated, such as trimmings, shavings, sawdust, etc. In addition, wood contains defects that require their removal, which reduces the efficiency of its use and increases significant environmental costs. One of the methods for the efficient use of wood is the production of wood composite materials, in particular, fiberboard and particleboard, OSB, MDF, etc. The technology for their manufacture involves the use of crushed wood, to which binders, salts, antiseptics, water repellents, and other substances are added. The resulting products can be categorized as biocomposite materials. Tarpaulin fabric, which consists of flax and cotton or jute fibers, is also widely used in the construction

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of mobile structures. They are twisted into threads and treated against rot, moisture, and other destructive factors by impregnation, and subsequently, by the method of linen weaving, they form a canvas. However, the above products are combustible materials and require protection from thermal action.

For the comprehensive protection of cellulose-containing materials from fire, a small number of fire retardants have been proposed, in particular, impregnating compositions and coatings on an inorganic and organic basis. However, their use for fire protection is challenging since it is difficult to impregnate a biocomposite due to the presence of a polymer component. The use of inorganic-based coatings, which contain bound water in their composition, which evaporates during heating and blocks the transfer of heat to the protected surface, is not effective because such a coating does not provide sufficient adhesive strength since it has a large temperature coefficient of linear expansion and crumbles during operation. The use of special organic-based coatings can form efflorescence; and under the influence of high temperature, toxic combustion products are released.

That is why intumescent fire-retardant complexes have appeared, which are environmentally safe, including green structures. These coatings reduce thermal conductivity as a result of transformation into a layer of foam coke under intense thermal action, delaying the ignition of combustible structures made of wood, textile products, and biocomposites for longer periods of time. And their heating for a given time does not allow high temperatures. Thus, the use of intumescent coatings based on a set of foam-suppressing substances, gas generators, and flame retardant requires fundamental research on their effect on the resistance of biocomposites to environmental operating conditions.

Therefore, the production of intumescent coatings for fire protection of biocomposites is relevant to ensure the fire resistance of building articles and predetermines the need for current research.

2. Literature review and problem statement

In [1] it is stated that due to the shortage of wood in some countries it is necessary to replace it with other raw materials, while using waste. The aim of the study was to use poppy straw waste for the efficient conversion of possible lignocellulosic materials – cellulose and particleboard. Their suitability for the production of composites is assessed on the basis of selected physical or mechanical properties. The Gurley tensile strength index and air permeability were determined as critical properties of pulp made from poppy straw using two delignification methods. The best mechanical properties, i.e., the tensile strength index, were achieved at 52.7 N·m/g for sodium pulp, but the nitrate-alkali method also showed corresponding values at 45.9 N·m/g. In the production of particleboard, parameters similar to those of bagasse or similar plants were achieved. However, nothing is said about the degree of accuracy being sufficient for application.

In [2], the effect of integrating technical lignin into chitosan-based bioplastics to improve their mechanical and thermal properties was evaluated. The solvent casting method was used to obtain chitosan-lignin bioplastics. The inclusion of lignin improved the antioxidant properties and mechanical strength of the bioplastic, and it functions as an ultraviolet blocking agent, as evidenced by UV protection studies. This indicates a decrease in the permeability of chitosan-lignin bioplastics by about four times. The introduction of lignin washed three times with HCl into chitosan-based bioplastics increased the tensile strength of the material by 36.41 % and the elastic modulus by 56.04 %. The antioxidant activity of chitosan-lignin bioplastics ranged from 75.80 % to 80.38 %, while that of pure chitosan was only 25.02 %. Thermal analysis revealed that the addition of lignin as an additive to chitosan-based bioplastics improved the thermal stability and flame retardancy of the bioplastics. This is indicated by the higher limiting oxygen index (LOI) values of 42 to 48 % for the chitosan-lignin bioplastics than for the control bioplastic (27 %), which has a UL-94 rating in the V-0 range. However, it is not stated to what extent the antioxidant, strength, and flame retardant properties of the chitosan-based bioplastics can be improved by the addition of lignin.

In [3], it is stated that the wood cell wall layer is essentially a biocomposite reinforced with periodically altered microfibrils, the mechanical properties of which are significantly affected by humidity. The function of the periodically graded microstructure of microfibrils in regulating moisture-induced stress and deformation is still unclear. By developing a shear-delay model, the authors successfully revealed the stress transmission properties of layers with periodically graded microfibrils at different humidity levels. It was demonstrated that the periodically graded microstructure contributes to a more uniform distribution of moisture-induced interfacial shear stress throughout the microfibril and significantly reduces the interfacial shear stress at the edges, which leads to a delay in the initiation of interfacial separation. In addition, it was found that the moisture-induced stress is non-monotonic and has a maximum value due to the fact that the polymers included in the matrix soften upon water absorption. Meanwhile, the length of different microfibril regions has been systematically studied, and the results indicate that the stress on the interface can be reduced by increasing the length of the graded regions, and a sufficiently large pitch does not affect the magnitude of the interfacial shear stress. In addition, the microstructure of the periodically graded fibril can effectively reduce the negative effect of debonding. However, it is not known to what extent the identified mechanisms contribute to the creation of fiber-reinforced composites that perform under wet conditions.

It was noted in [4] that composites are usually composed of high-strength textile materials (TRMs) based on synthetic fibers embedded in a cement matrix to improve the strength and stiffness of the resulting composites. However, natural coconut fiber fibers have inherent disadvantages, including their hydrophilic nature and lower tensile strength/stiffness. To overcome these problems, coconut fiber yarns have been prepared by coating (one, two, and three layers) with PLA (polylactic acid) suspension to obtain biocomposites. The average tensile strength of raw coir yarn (without polymer coating) is 42 MPa, which increased by 38 % with a single layer of PLA coating, 98 % with two layers, and 107 % with three layers, respectively. In addition, the initial tangent modulus of raw coir yarn coated with three layers of PLA suspension improved by 121 %. Fractographic analysis revealed the tensile cracking of the coir yarns, which showed significant changes according to the number of PLA layers applied. Finally, the treated coir yarns were used as reinforcement together with pre-tensioning. Pre-tensioned coir yarns with TRM pre-tensioning increased the tensile strength by 133 % and the initial tangent modulus by 139 % compared to the control. However, it is not stated how other types of biocomposites with low moisture content are prone to ignition.

In [5], the thermal barrier properties of fiber-reinforced composites with heat-reflecting surfaces for building applications are investigated. Biocomposites made of natural cotton fiber in white and four different colors, such as red, yellow, blue, and black, were designed by using compression molding technology. Among the composites studied, the white cotton composite, due to its reflective surface, has the lowest thermal conductivity of 0.0687 W/m·K, which was the maximum for its black counterpart with a value of 0.0823 W/m·K. The white composite, on the contrary, showed a higher thermal conductivity (0.0582 m^2·K/W) than the black one (0.04862 m^2·K/W). The evaluation of radiative heat resistance using an incandescent lamp and sunlight showed the excellent resistance of the white composite to radiant heat transfer due to its high reflection of electromagnetic radiation. In addition, thermogravimetric analysis revealed adequate thermal stability with a similar trend in the degradation structure of the composites at elevated temperatures, confirming the insignificant effect of color on thermal stability. The overall results of the study indicate that fiber-reinforced composites with reflective (white) surfaces can significantly resist conductive and radiant heat transfer than colored cotton materials. However, it is not stated how the resulting thermal insulation panels are used to reduce heat load and maintain a favorable indoor temperature.

Study [6] reports an approach to improve the fire resistance and smoke suppression of poly(lactic acid) (PLA) composites, facilitating their application in various industries. Flax fibers (FF) were surface-treated with an organic-inorganic hybrid flame retardant (FR). The process involves ozone treatment of flax fiber (FF), followed by gallic acid (GA) covalently immobilized on the fiber surface (FF-GA), and finally, hybrid FR iron phenyl phosphonate complexed with the phenolic groups of the GA units (FF-GA-FeP). Fourier transform infrared (FT-IR) analysis of FF-GA-FeP confirmed the presence of specific absorption associated with the applied FR coating. Scanning electron microscopy combined with energy dispersive X-ray spectroscopy (SEM-EDS) revealed changes in fiber morphology and confirmed the incorporation of iron and phosphorus. Solid-state nuclear magnetic resonance (SSNMR) and WAXS X-ray microscopy showed that the crystallinity of the fibers did not significantly affect the derivatization. Microwave atomic emission plasma spectroscopy (MP-AES) revealed a precise iron loading of 0.1 wt %. The use of FF-GA-FeP as a reinforcement in PLA-based composites (PLA/FF-FeP) resulted in improved thermal stability and fire resistance, as revealed by thermogravimetric analysis (TGA) and cone calorimetry (CCT) tests. Reductions in peak heat release rate (pHRR), total smoke release (TSR), specific extinction area (SEA), and flame spread index (FPI) of 5, 87, 68, and 9.5 %, respectively, were achieved for PLA/FF-FeP compared to untreated flax fiber-reinforced PLA (PLA/FF). In addition, preliminary tensile tests indicate changes in tensile strength and a slight increase in stiffness of PLA/FF-FeP.

Biopolymer-based soil composites (BSCs), as described in [7], are a new class of cement-free building materials that utilize biopolymer binders, many of which are derived from waste streams from major industrial plants. BSCs were manufactured by mechanical destruction of the virgin material followed by solvent re-introduction, re-mixing, and re-shaping. The compressive strength of the recycled lignin-based BSC was higher than that of the BSC made from virgin ingredients. To understand the microstructure of the lignin-based BSCs, a series of X-ray micro-CT images of the test products were obtained. The images acquired using the micro-CT method reveal differences in the microstructure of the recycled samples, indicating an increased association between lignin and aggregate particles. However, questions remain regarding the feasibility of recycling and the determination of the mechanical properties of the BSCs.

Advances in the world of materials science are driving the emergence of a new generation of sustainable materials [8]. Natural fiber (NF) biocomposites are emerging as valuable alternatives to conventional materials for engineering applications such as construction, automotive, and aerospace, due to their exceptional mechanical properties, light weight, low carbon footprint, energy efficiency, and cost-effectiveness. These outstanding properties have made them more desirable for engineering applications. However, the main focus has been on lignocellulosic fibers, neglecting other sources such as keratin, fibrin, and microbial fibers. Only a few reviews address the relationship between the structure and properties of all classes of natural fibers, such as lignocellulosic (plant), keratin, and fibrin (animal), and microbial (mycelium) fibers. Although NFs have outstanding potential from an economic, technical, and environmental perspective, they have limitations such as fiber-matrix incompatibility and moisture damage. These limitations make it difficult to use NFs as reinforcement for various material systems.

Paper [9] states that wood can be processed and transformed into a variety of biocomposites. The results show that advanced biocomposites will combine wood, natural biofibers, and non-biomaterials to create synergistic hybrid materials that significantly exceed the performance of current biocomposites; be renewable, recyclable, and completely environmentally friendly; and provide superior performance and serviceability beyond current biocomposites; and be stronger, dimensionally stable, moisture-resistant, and fire-resistant. This suggests that the next generation of advanced wood-biocomposites should provide highly efficient construction and specialty products that simultaneously contribute to resource conservation and environmental sustainability, while providing improved performance, long-term performance, increased durability, and value.

Study [10] provides an overview of the types of flame retardants commonly used, as well as a review of studies conducted to determine the fire resistance of composites. Several tools and standards used to determine the fire behavior of composites are also described in detail. Biochar (especially produced at high pyrolysis temperatures) is very resistant to ignition and thermally stable due to the extensive cross-linking network between adjacent aromatic carbon layers. Its incorporation into polymer composites has advantages in terms of both fire resistance and mechanical properties. The inherent fire resistance and charring ability of wool (a natural protein fiber) has been used to design composites that exhibit the highest degree of fire resistance (rating V0 in UL94 tests). Finally, wheat gluten, a by-product of the grain industry, has shown potential for fire resistance and thermal stability. However, the fire-resistant properties of gluten can be made even stronger by using other additives (e.g., silica).

The combustion of biocomposites, as stated in [11], can potentially create life-threatening conditions in buildings, leading to significant human and material losses. Additives known as flame retardants (FRs) are commonly used to improve the fire resistance of wood and biocomposites, textiles, and other industries in order to expand their application areas. This prac-

tice is now very common in the construction industry due to strict fire safety regulations in residential and public buildings. The aim of the study was to report and discuss the latest advances in the development of fire-resistant biocomposites. To build 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 FR additive for the production of high-performance biocomposites with improved technological and fire-fighting properties was also discussed in detail. However, it is not indicated how these compositions can be used for other materials.

Renewable and biodegradable polylactide (PLA), which is reported in [12], 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. For polyphosphoramides, despite their high flame retardant efficiency, their chemical synthesis often generates chemical waste as by-products. The authors report an atom-economical and highly efficient oligomeric P/N flame retardant (APN) prepared by a soft Michael polymerization without 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 strength of flame-retardant PLA is increased by 85 % compared to pure PLA, while maintaining both tensile strength and thermal stability. The work proposes an atom-economic strategy for the synthesis of highly efficient P/N flame retardants for use in the creation of flame-retardant PLA.

Our review of the literature [3–10] demonstrates that biocomposites are an environmentally friendly and inexpensive alternative to petroleum-based materials and fossil deposits. They are becoming more and more popular due to good mechanical properties, low production costs, recovery ability, and biodegradability. However, they are flammable products. Therefore, establishing the parameters of the flame resistance of biocomposites and the influence of coatings on this process necessitated the need for research in this area.

3. The aim and objectives of the study

The aim of our work is to establish the regularities of the formation of flame-retardant biocomposites when they are treated with an intumescent coating. This makes it possible to expand the scope of application of biocomposites on objects of various purposes.

To achieve the goal, it was necessary to solve the following tasks:

– to conduct a study on the interaction of cellulose-containing materials with an intumescent coating;

– to determine changes in the flammability process when biocomposites are treated with an intumescent coating under the influence of high temperature.

4. The study materials and methods

4. 1. The object and hypothesis of the study

The object of our study is the process of forming a thermal insulation layer of foam coke during thermal action on a biocomposite with the presence of an intumescent coating. The scientific hypothesis is to reduce the flammability of the biocomposite when interacting with a high-temperature flame and to establish the thermal insulation properties of the foam coke layer.

In the process of the study, it was assumed that the influence of external conditions on the object of research and the course of the fire resistance process of the biocomposite is constant, and as a simplification, it was assumed that the temperature, humidity, and pressure do not change.

4. 2. The materials under study used in the experiment

The study was conducted using samples of pine wood measuring 150×60×30 mm, plywood 150×60×12 mm, chipboard 150×60×20 mm, and MDF measuring 150×60×20 mm, with a density of about 550 kg/m^3. To establish the fire-retardant efficiency of the textile material, samples of canvas fabric measuring 220×170 mm were used. To study the fire resistance of the biocomposite, a coating "FIREWALL-WOOD" (made in Ukraine) was applied to the surface of the above samples of wood materials and textiles, which is capable of swelling under high temperature. The coating consumption was about 250.0 g/m^2.

After drying to a constant mass, the treated biocomposite samples were tested for interaction with the coating components and thermal destruction.

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

To determine the patterns of interaction of wood and textile products based on plant raw materials with an intumescent coating, the structure change was determined by Fourier transform infrared spectroscopy (FTIR) and the adhesion resistance of the coating to wood. The fire resistance of wood-based biocomposites was determined by determining the flammability group in accordance with DSTU 8829, and for textile materials, the flammability group of fabric-based biocomposites was determined in accordance with DSTU 4155.

Fourier transform infrared spectroscopy (FTIR) was performed taking into account [13]. Research method: 0.5 mg of a sample crushed from 70 mg of potassium bromide (split from a single crystal). A tablet was compressed from the resulting mixture under a pressure of 10 MPa, achieving maximum optical transparency (to reduce scattering). The spectrum was recorded in the range of 4,000–400 cm^{-1}, with an optical slit width of 4 cm^{-1}, the spectrum was averaged over 12 scans. The analysis was performed on a Spectrum One spectrometer (Perkin Elmer).

The determination of the adhesion strength of the polymer coating shell to wood was performed in accordance with ASTM D4541-22. Its essence was to glue the stop to the polymer coating shell of the wood sample and after drying and exposure, the stop was loaded to the tear with the determination of its level of force. The elastic adhesive sealant "Fix All" produced in Ukraine was used as the glue.

5. Results of determining the fire resistance of a biocomposite protected against fire by an intumescent coating

5. 1. Results of investigating the interaction of an intumescent coating with cellulose-containing materials

Fig. 1, 2 show the IR spectra of the studied biocomposite samples.

Analysis of the FTIR spectra of wood and fabric samples indicates the similarity of the transmission bands. The largest markers are the absorption bands in the wavelength range of 2,400–3,700 cm^{-1}. In the case of untreated wood, the transmission bands of the IR spectrum in the range of 3,700–3,100 cm^{-1} characterize the stretching vibrations of various types of hydroxyl groups in lignin, in particular, the stretching vibrations of aliphatic hydroxyl groups, as well as the OH groups of cellulose and xylan. All hydroxyl groups are involved in hydrogen bonds. When the wood is impregnated, the transmission bands of OH groups in the above range disappear, which indicates the emergence of a chemical bond. The same applies to coated wood. The region of 3,000–2,800 cm^{-1} characterizes the symmetric and asymmetric C–H valence vibrations in the methyl and methylene groups of lignin. Valence vibrations of C–H bonds in the methylene and methine groups of cellulose appear in the region of 3,000–2,800 cm^{-1}.

In xylan, C–H valence vibrations of the CH_3, CH_2, and CH groups with a maximum at 2,930 cm^{-1} are manifested. Leveling of the region 3,000–2,800 cm^{-1} in cases of impregnation of wood or wood with a coating is not determined.

Similar spectra are observed for untreated, impregnated, and coated fabric. The nature of the interaction is similar, as evidenced by the transmission bands in the wavelength range of 2,400–3,700 cm^{-1}.

Fig. 3 and Table 1 demonstrate the results of our study on the adhesion of the intumescent coating to wood and particleboard samples.

Table 1

Adhesion strength of the coating to the particleboard surface

Sample	Adhesion strength, MPa	Nature of the destruction of the coating
Wood	0.25	Destruction occurred along the coating
Particleboard	0.45	Destruction occurred along the coating

From Fig. 3 it is established that the nature of the fracture of the samples occurred along the coating.

As can be seen from Table 1, the value of the adhesive strength of the polymer coating on wood treated with an intumescent coating is 0.25 MPa, the nature of the failure occurred along the polymer coating with a detachment area of about 25 %. For particleboard treated with an intumescent coating, the value of the adhesive strength is about 0.45 MPa, while the failure occurred along the polymer coating with a detachment area of about 10 %.

Considering the non-rigid structure of the textile material, the determination of the adhesion ability of the coating to the textile material was not carried out.

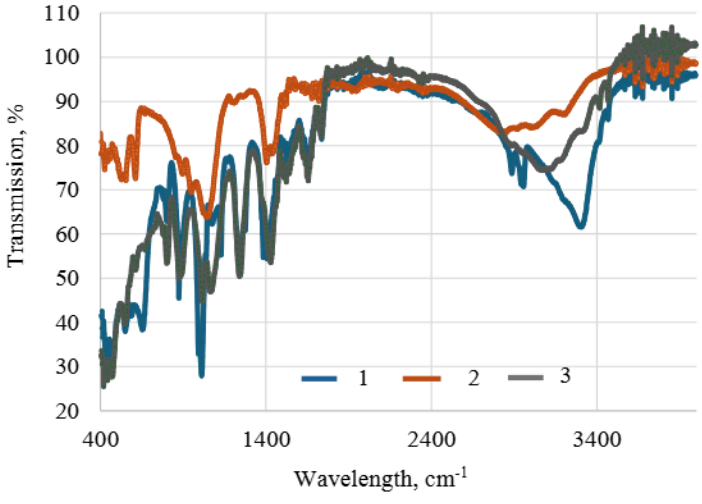


Fig. 1. Absorption spectra of wood-based biocomposite samples: 1 — pine wood; 2 — wood treated with flame retardants; 3 — wood treated with a coating

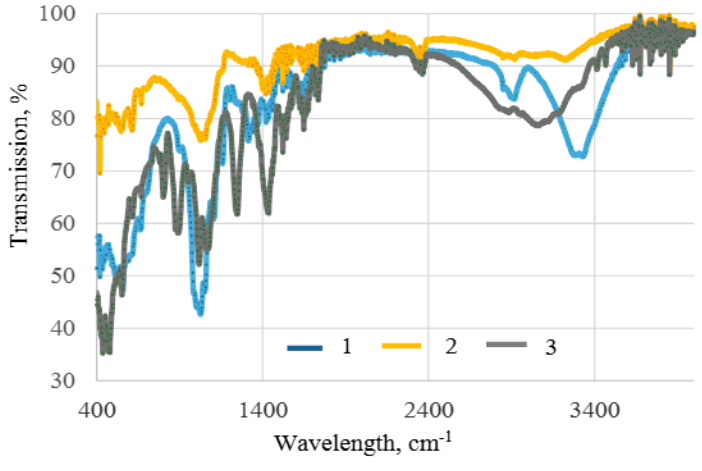
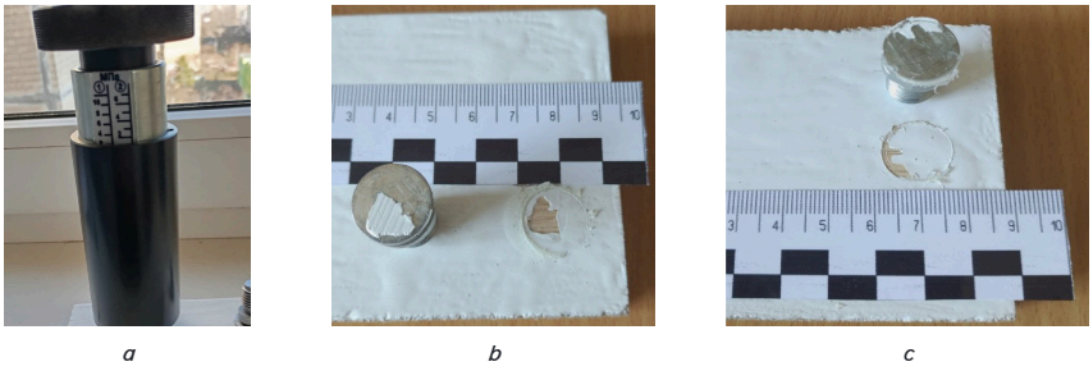


Fig. 2. Absorption spectra of biocomposite samples based on textile fibers: 1 — tarpaulin fabric; 2 — tarpaulin fabric treated with flame retardants; 3 — tarpaulin fabric treated with a coating



a *b* *c*

Fig. 3. Results of determining the adhesion strength of the intumescent coating to the samples: *a* — adhesion research process; *b* — nature of the stop detachment for wood; *c* — nature of the stop detachment for particleboard

5. 2. Experimental studies on the flammability group of biocomposites and their results

The results of studies on the experimental determination of the flammability group of fire-resistant biocomposites are shown in Fig. 4–7.

Fig. 4. The combustion process of biocomposite samples at fire exposure

Fig. 5. Samples of wood biocomposites after thermal treatment: 1 – MDF, 2 – particleboard, 3 – wood, 4 – plywood

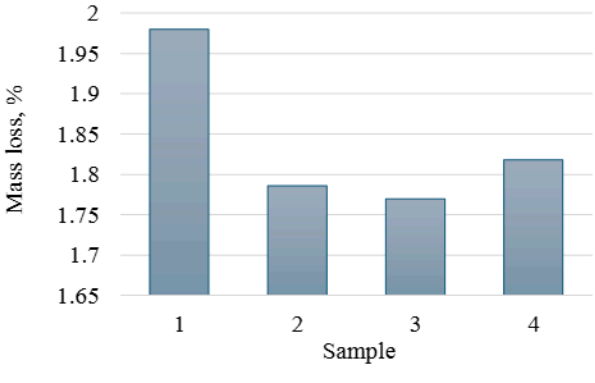


Fig. 6. Results of mass loss by samples Dm, % of biocomposites: 1 – plywood; 2 – chipboard; 3 – MDF; 4 – wood

Studies have shown that at the initial temperature of gaseous combustion products T=200 °C, when the burner flame was applied to samples of fire-resistant biocomposites, the temperature of gaseous combustion products was T≤185 °C. Even greater fire resistance was shown by the results of mass loss after thermal action (Fig. 6), which was less than 2 %. During thermal action, the coating formed a layer of foam coke more than 20 mm.

To determine the fire resistance of a biocomposite based on tarpaulin fabric, studies were conducted on the effect of the burner flame on it, which are illustrated in Fig. 8.

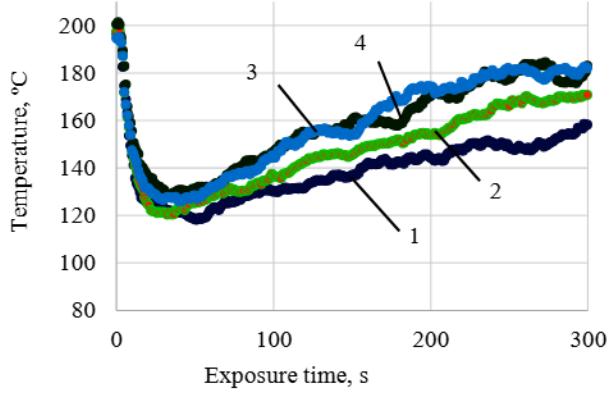


Fig. 7. Dynamics of flue gas temperature increase during biocomposite tests: 1 – wood; 2 – chipboard; 3 – MDF; 4 – plywood

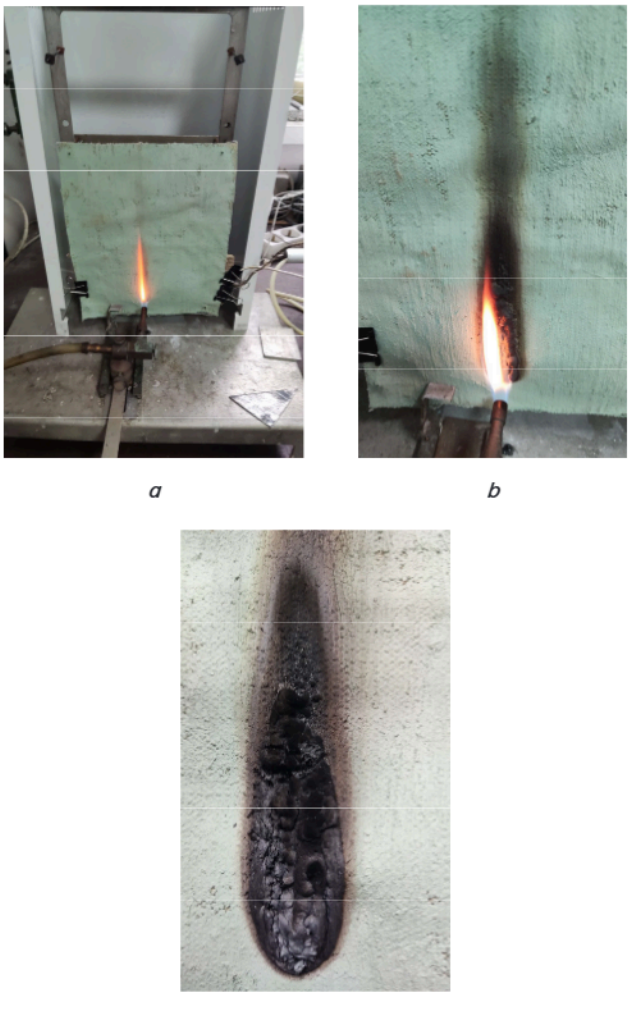


Fig. 8. Test results for determining a biocomposite based on tarpaulin fabric: *a* – test structure, *b* – burner effect on the material, *c* – coke foam layer after combustion

Studies have shown (Fig. 8) that when the burner flame was applied to the biocomposite, intensive swelling of the coating began, which led to the formation of a thermal insulation layer of foam coke with a thickness of more than 9 mm; the fabric did not ignite.

6. Discussion of results based on investigating the process of fire protection of wood with reactive coating

When studying the process of interaction of fire retardants with biocomposites of wood and textile products, as follows from the results obtained (Fig. 1, 2), the formation of chemical bonds is natural. This is due to the fact that when biocomposites are treated with chemicals, the transmission bands of OH groups in the range of 3,700–3,100 cm^{-1} disappear, which indicates the occurrence of a chemical bond.

It should be noted that the presence of an intumescent coating on biocomposites leads to the formation of an elastic film on the surface of the polymer shell that is resistant to mechanical vibrations. Apparently, such a mechanism of influence of the elastic film is the process control factor due to which the stability of the coating is maintained. The value of the adhesion strength of the polymer shell on wood is quite large and the nature of the destruction occurred along the polymer shell with a separation area of less than 25 %. This indicates the formation of an elastic film on the surface of the wood. In this sense, the interpretation of the results of determining the quality of the film takes place, namely the absence of defects on the surface [14, 15]. This means that taking into account this fact opens up the possibility of effectively regulating the fire resistance of biocomposites directly under the conditions of serial industrial production.

Comparison of experimental studies (Fig. 4–8) on the determination of the flammability group of wood-based biocomposites indicates the inhibition of heat transfer processes, since under the action of the burner flame, the temperature of the gaseous combustion products did not exceed 185 °C, the results of mass loss were less than 2 % and formed a layer of foam coke over 20 mm. In this sense, the interpretation of the results of determining the fire resistance of a biocomposite based on tarpaulin fabric also has a meaning since under the action of the burner flame, intensive swelling of the coating began, which led to the formation of a heat-insulating layer of foam coke over 9 mm. Thus, unlike previous studies [2, 5, 6, 11], in which much attention was paid to the use of flame retardants, our study analyzes the intumescent coating that is part of the structure of the biocomposite. However, unlike the results of studies reported in [16, 17], our data on the inhibition of temperature transfer to the biomaterial and the influence of the intumescent coating on the process of thermal resistance with the formation of a thermally insulating layer of foam coke allow us to state the following:

– the main regulator of thermal insulation is not so much a change in the direction of wood decomposition towards the formation of non-combustible gases and a difficult-to-burn coke residue under the influence of high temperature;

– a significant impact on the protection of biocomposites during the application of a reactive coating is achieved by inhibiting oxidation in the gas and condensed phases with the formation of a heat-protective coke layer on the surface of the material.

Such conclusions warrant greater validity of the results since the studied biocomposites were tested for reaction to high temperature, which reflects real circumstances during operation. The experimental results showed that this approach has a certain potential, which is manifested in the thermal insulation of the material [18]. Determination of the swelling value during testing demonstrates how the foam coke layer heat-insulates the surface of the biocomposite.

Our results for determining the fire resistance of biocomposites have limitations in determining the formed foam coke layer and determining the swelling rate during testing. In addition, the response of the biocomposite to the influence of high flame temperature may give insufficiently predictable indicators due to the small amount of data on the reduction of the swelling value of the coating, which limits the use of the results. The disadvantage of the applied experimental approach is a certain complexity, which may limit the determination of the fire resistance effect of the biocomposite. However, thanks to fire tests, it is possible to obtain reliable results that allow us to establish the mechanism of operation of the reactive coating. In particular, they can be focused on identifying the moment of time from which the decrease in fire resistance and ignition of the biocomposite begins under the influence of high temperature. Further development of the study area on devising technologies for designing fire-resistant biocomposites can reveal potentially interesting areas of further research, in particular, in the optimization of experimental data on the development of coating formulation.

7. Conclusions

1. Based on our results of experimental studies on the interaction of wood-based biocomposites and textile products with reactive coatings, it was established that chemical bonds arise when wood and fabrics are treated with flame retardants. This mechanism of action is characterized by symmetric and asymmetric valence vibrations of C–H in the methyl and methylene groups of lignin and cellulose. When determining the adhesion strength of the polymer shell on wood treated with an intumescent coating of 0.25 MPa, the nature of the failure occurred along the polymer shell with a separation area of about 25 %. For particleboard treated with an intumescent coating, the adhesion strength value is about 0.45 MPa, while the failure occurred along the polymer shell with a separation area of about 10 %.

2. According to the results of the experimental determination of the flammability group of wood-based biocomposites, it was found that when a burner flame was applied to samples of fire-resistant biocomposites, the temperature of the gaseous combustion products did not exceed 185 °C. Even greater fire resistance was shown by the results of the mass loss after thermal action, which was less than 2 %. Under thermal action, the coating formed

a layer of foam coke more than 20 mm. When a burner flame was applied to a biocomposite based on tarpaulin fabric, intensive swelling of the coating began, which led to the formation of a heat-insulating layer of foam coke more than 9 mm in size, ignition and flame spread did not occur.

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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