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Content

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The process that forms the properties of fire-resistant biocomposites based on wood sawdust and a binder from a mixture of gypsum and an intumescent coating based on PVA dispersion has been investigated. The task addressed is to ensure the stability of biocomposites based on a gypsum binder to changes under operating conditions. This is important since the production of biocomposites from renewable sources for construction is relevant.

It has been proven that when thermally exposed to the biocomposite samples, no ignition occurred, the maximum temperature of the flue gases was about 84°C. When using a gypsum binder, a non-combustible structure was formed on the surface of the biocomposite, which prevented the sample from igniting. For a biocomposite based on a binder from a mixture of gypsum and an intumescent coating based on PVA dispersion (hybrid binder), charring of the sample surface is characteristic, which prevents its ignition.

In addition, the results of determining the process of wetting biocomposites with test liquids showed that the obtained solids belong to hydrophilic materials with high water wettability. Analysis of the results of experiments on water absorption of biocomposites reveals that the maximum mass gain of the biocomposite on gypsum binder under the influence of moisture was almost 27% and the main increase in moisture occurred in the first 5 days of exposure. The mass gain of the biocomposite samples on hybrid binder was less than 10% due to the formation of a shell on the surface of sawdust. The value of the compressive strength of biocomposites showed that the sample formed on gypsum binder is significantly fragile. However, for the biocomposite formed on hybrid binder, the ultimate strength is 1.88 MPa, which is provided by the adhesive properties of the intumescent coating.

Thus, there are grounds to argue about the possibility to effectively design operationally stable biocomposites for construction

Keywords: fragility of gypsum products, hybrid binder, wood sawdust, coke layer, fire resistance

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EVALUATING DEEP LEARNING ARCHITECTURES FOR CO_2 EMISSIONS FORECASTING: TCN, LSTM, AND HYBRID APPROACHES WITH HYPERPARAMETER OPTIMIZATION

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1. Introduction

Composites using gypsum as a matrix are one of the oldest materials for construction. They are used for interior wall and ceiling finishing due to their numerous advantages, such as low cost, energy consumption, and fire resistance. The main disadvantage of gypsum-based composites is fragility, poor mechanical properties, low water resistance, acoustic and thermal insulation properties, as well as shrinkage after thermal exposure. Therefore, the level of use of gypsum in construction by-products remains low.

To expand the scope of application of gypsum products, it was proposed to include fibrous materials in their composition, since due to their hardness, durability, and strength they can be used to create gypsum composites. In addition, they can improve the properties of gypsum and overcome the disadvantages, and given the use of environmentally friendly materials, the use of natural fibers has become a common practice due to their attractive characteristics. The main advantage of using natural fibers is high energy absorption, which is a result of low modulus of elasticity.

The addition of silicate cement as an inorganic modifier and polyvinyl alcohol solution as a strengthening agent to gypsum increases both strength and reduces moisture absorption. However, these additives do not provide fire resistance of gypsum biocomposite and require an increase in the amount of gypsum, which leads to an increase in the density of the product. It is known that the use of flame retardants such as phosphogypsum, compared to commercial gypsum, showed a slight improvement in fire resistance, since impurities with high water attraction are present in the structure of the biocomposite, which affected the high temperature retardation. The effectiveness of the use of intumescent coating based on polyvinyl acetate dispersion has been established high adhesion to cellulose-containing materials, and due to the action of flame retardants, it is possible to significantly influence the combustion of the biocomposite, due to the directed formation of foaming and coke-forming additives.

Therefore, the formation of fire-resistant biocomposites based on gypsum is associated with a significant decrease in the peak heat release rate, and the use of intumescent coating is associated with the risk of changing the structure of the biocomposite, which will negate the result obtained. This requires conducting research to determine the compatibility of the biocomposite components and their stability during operation. In addition, it is necessary to focus on compliance with the technological regime, quality, and proper preparation for the use of the resulting biocomposite.

Thus, research aimed at establishing the effectiveness of the formation of a biocomposite based on gypsum and changes in its structure when adding an intumescent coating, which are necessary to ensure fire resistance, is relevant.

2. Literature review and problem statement

In [1], the results of research on the development and optimization of environmentally friendly biocomposite ceiling tiles by partially replacing gypsum with pearl millet waste combined with wheat flour waste (WWF) and waste paper are reported. It is shown that the Taguchi method was used for experimental design by varying key parameters such as gypsum, pearl millet seed coating (PMSC), and ceiling tile thickness. The signal-to-noise ratio (S/N) was used to determine the optimal composition, and analysis of variance (ANOVA) with regression analysis determines the significance of each factor for thermal conductivity and flexural strength. The optimized composition for the minimum thermal conductivity (0.065 W/m K) was determined as 45% PMSC and 10% gypsum at a thickness of 12 mm. For maximum flexural strength (1.24 MPa), the optimal mixture was 55% PMSC and 30% gypsum at a thickness of 14 mm. The constructed regression models showed a predictive value of R2 of 96.90% for thermal conductivity and 94.44% for flexural strength, as well as an error below 3%, confirming the reliability of the approach. This study is original and presents biocomposites from pearl millet waste as an environmentally friendly alternative to gypsum ceiling tiles. These tiles have practical value for ceilings, partitions, and decorative finishes in different geographical regions. However, there are unresolved questions as to the extent to which they contribute to environmental sustainability and energy-efficient building solutions. The reason for this may be the objective difficulties associated with establishing the thermal insulation properties of the resulting products, which makes the relevant studies incomplete.

An option to overcome these difficulties could be work [2], which addresses the need for materials applications by developing gypsum-based composites enriched with vermiculite and recycled rigid polyurethane powder (RPU) using a mixing-pressing-sintering methodology. Gypsum-based composites were chosen due to their cost-effectiveness, recyclability, structural stability and sound-absorbing properties, all with minimal environmental impact. High-resolution scanning electron microscopy (HR-SEM) and Fourier transform infrared spectroscopy (FTIR) were used to analyze the size, structure, homogeneity, and presence of organic and inorganic compounds. Using response surface methodology (RSM) for optimization, an ideal noise reduction coefficient (NRC) formula was determined with an optimal mixture of 5.3 wt. % vermiculite and 6.5 wt. % RPU, achieving an NRC value of 0.3628. Acoustic modeling using COMSOL Multiphysics, based on the Johnson-Allard model, demonstrated that the optimized composite effectively reduced the sound pressure level by 17–58 dB in the frequency range from 200 to 2000 Hz. However, no optimal solutions were found for use.

In [3], it was noted that composites with a wood chip content of up to 90% were developed by compression molding, and the mechanical, acoustic, and thermal properties were investigated. In addition, malleated polypropylene (MAPP) was used (1–5% w/w based on the wood chips used) as a compatibilizer, and changes in properties were recorded. An increase in tensile strength of up to 300% was observed in the presence of 5% compatibilizer. The tensile strength characteristics of composites containing MAPP were higher than those of commercially available medium density plywood boards, as well as gypsum-based ceiling boards. The addition of MAPP did not change the thermal conductivity, but reduced sound absorption. Wood chip reinforced PP composites containing MAPP demonstrate extremely high properties and can replace particleboard, fiberboard and other building materials currently used. The use of wood waste also leads to environmentally friendly, sustainable, and inexpensive building materials. However, it is not stated how the resulting biocomposite is exploited.

In study [4], fibers were extracted from the stems of *Megaphrynium macrostachyum* by biological and chemical maceration. The chemical fibers were bleached with 2.5% sodium hypochlorite (NaClO) solution. The feasibility of using these fibers as reinforcement in gypsum-based biocomposites for construction was analyzed using three-point bending tests. Chemical analysis revealed a cellulose content of more than 56 wt. % within the usual range (50–85 wt. %) for reinforcing fibers. SEM images showed that bleaching cleaned the surface of the fibers. Physical analysis using gravimetric analysis showed that the bleached fiber had the lowest density (1.01 g cm^{-3}), fineness (5.2 tex), and water absorption (64 wt. %). In addition, the highest thermal stability (237°C) was obtained for the chemical fiber. Young's modulus and tensile strength, evaluated according to ASTM D3822-07, were dispersed and depended on the fiber diameter, with the highest values obtained for chemical fiber (6.4 GPa and 251 MPa). In contrast, gypsum composites with a volume fraction of 1.5% bleached chemical fiber had the highest stiffness (258 MPa) and flexural strength (5 MPa). However, the conditions of use of the obtained gypsum-based biocomposites were not given.

In [5], a bioengineered building material based on hemp chips and gypsum was investigated. A low-density material with densities of 200, 300, and 400 kg/m^3 was designed. A simple but reliable production technology was used. For the first time, a binder for biocomposites obtained from phosphogypsum was used, and its properties were compared with commercial gypsum. A CO_2-negative building material was developed with a capture capacity of up to 92 kg CO_2-eq/m^3. Both physical and mechanical properties were investigated. Thermal conductivity ranged from 0.058 to 0.101 W/(m·K) and compressive strength ranged from 0.10 to 0.57 MPa. Biodegradation test results showed that pH 5.60–6.55 for the biocomposites promoted rapid mold growth. Mold growth was slightly lower for composites with higher gypsum content, while phosphogypsum induced faster mold growth. *Cladosporium*, *Rhizopus*, *Chaetomium* and other mold fungi were detected on the samples even at the early stage of testing, raising serious concerns about the limited application of this gypsum-based biocomposite in dry conditions. But the impact of this biocomposite on the environment is not mentioned.

The work presented in [6] aims to reduce the negative environmental impact of the construction industry by providing biocomposites with low environmental impact through efficient use of materials through 3D printing. Agricultural waste – hemp chips – is used in these materials as a filler together with three different types of fast-setting binders – magnesium, calcium sulfoaluminate (CSA) and gypsum-based. The study determines the setting time and compressive strength of these binders, as well as the formation of biocomposites with different densities for different applications; extrusion tests and a preliminary life cycle assessment (LCA) are also carried out. The results show that biocomposites with hemp fire and fast-setting binders have potential applications in 3D printing due to their dimensional stability and scalability, as well as relatively high compressive strength. This allows them to be used as load-bearing materials at high densities and as thermal insulation materials at low densities. Preliminary LCA results show that CSA and gypsum binders have the lowest environmental impact among the binders considered. However, it is not stated how the low binder content affects printability.

In [7], the research focused on the creation of a biocomposite material that would be used in buildings for thermal insulation. The effect of hemp fibers on water absorption, thermal conductivity, and mechanical characteristics of gypsum-based materials was experimentally investigated. The results showed that in gypsum-based materials, the thermal conductivity decreases with the gradual increase in the concentration of hemp fibers. This clearly shows that the loading of hemp fibers can lead to a significant effect on the thermal and mechanical properties of the composites. The flexural and compressive strengths of the composites are enhanced by adding sufficient fibers. These newly developed composites exhibit good mechanical and thermal properties, which allows them to be used for insulation materials. However, the water absorption characteristics of the resulting composites have not been observed.

The study reported in [8] aims to develop a new biocomposite material that could be used as thermal insulation in buildings. For this purpose, it was necessary to experimentally investigate the effect of date palm fibers DPF (*Phoenix dactylifera L.* from the Biskra oasis in Algeria) on the thermal conductivity, water absorption, and mechanical properties of gypsum-based materials. Biocomposites containing different DPF filler contents and two different DPF sizes were prepared. The results showed that the thermal conductivity of gypsum-based materials decreases with increasing DPF concentration. It was not noted that the DPF loading may have a greater effect on the mechanical and thermal properties of composites than the effect of fiber size. The compressive and flexural strengths of biocomposites can be improved by adding a sufficient amount of fibers. This new type of biocomposite exhibits good thermal and mechanical characteristics, which allows it to be used as thermal insulation materials. However, their impact on the ecosystem is not mentioned.

In study [9], gypsum-based bio aggregate composites (BACs) were developed and tested. Phosphogypsum was evaluated as an alternative binder. The aim of the study was to evaluate the fire resistance of BACs based on gypsum and phosphogypsum as binders. In the study, the amount of binder was varied and BACs with densities ranging from 200 to 400 kg/m^3 were tested. For the first time, the fire resistance of a commercial hemp chip BAC based on gypsum and phosphogypsum was evaluated using a cone calorimeter. The results show that the role of gypsum content has a significant impact on the fire resistance. The ignition time increased from 14 to 19 s, and the peak heat release rate decreased by 57%. Phosphogypsum binder, compared to commercial gypsum, showed a slight improvement in fire resistance, since impurities with high water attraction are present in the PG structure. However, it is not stated how phosphogypsum affects the mitigation of flame action.

In [10], alternatives to lime-hemp concrete are considered that would achieve similar thermal properties with equivalent or lower environmental impact. As alternatives, binders such as gypsum, geopolymers, and starch are proposed due to their performance characteristics and low environmental impact, and the available studies are summarized and discussed in this article. The summarized results show that with gypsum and geopolymer binders, low-density thermal insulation biocomposites with densities of 200–400 kg/m^3 and thermal conductivity (λ) of 0.06–0.09 W/(m × K) can be obtained. However, using starch binder, it is possible to produce environmentally friendly building materials with densities of approximately 100 kg/m^3 and thermal conductivity (λ) of up to 0.04 W/(m × K). In addition, a preliminary life cycle assessment was conducted to assess the environmental impact of the biocomposites considered. The results show that such biocomposites have a low environmental impact, similar to lime-hemp concrete. However, it is not stated how the material is operated.

In [11], agricultural waste (TR) was combined with ammonium polyphosphate (APP) as an acid source and melamine (MEL) as a gas source in a mass ratio of 1:3:1.

This led to the formation of a synergistic flame retardant TR/APP/MEL (TRAM), which was incorporated into biomass-based polybutylene succinate (PBS) to obtain flame retardant biocomposites. To further improve the carbonization efficiency, zinc oxide (ZnO) was introduced as a catalyst, which allowed the preparation of a second IFR system, TR/APP/ZnO (TRAZO). Combustion tests showed that the inclusion of 30 wt. % TRAM in PBS increased the limiting oxygen index (LOI) from 22% (pure PBS) to 40% and achieved a UL-94 V-0 rating without leakage. Thermogravimetric analysis (TGA) confirmed the improved thermal stability, with the char residue increasing from 1.98 wt. % to 14.39 wt. %. In addition, the TRAZO-based composite containing only 20 wt. % IFR also achieved a UL-94 V-0 rating and LOI of 30%, indicating that the introduction of ZnO effectively eliminates the dripping of the PBS composite by graphitized char formation during combustion, thereby improving the fire resistance. Cone calorimetry (CCT) results further demonstrated that TRAM significantly reduces heat release and smoke production. These results highlight the potential of TR-derived IFRs, including TRAM and TRAZO, as environmentally friendly, halogen-free, and effective flame retardants for biodegradable polymers.

In [12], a flame retardant coating was proposed on wood by the layer-by-layer (LBL) self-assembly method using chitosan (CS), graphene oxide (GO), and ammonium polyphosphate (APP). Characterization by scanning electron microscopy (SEM) and Fourier transform infrared spectroscopy (FT-IR) showed that the polyelectrolytes CS-GO and APP were successfully deposited on wood, and the amount of deposition increased with the increase in the amount of LBL. Thermogravimetric analysis revealed that the CS-GO-APP coating could reduce the initial and maximum thermal decomposition temperatures of the coated wood. In addition, it significantly increased the char residue, which may be due to the earlier degradation of CS and APP and the effective thermal barrier of the incorporated GO, thereby enhancing the thermal stability of the modified wood. The results of the limited oxygen index (LOI) and cone calorimeter analysis of the pure and coated wood showed that the fire resistance was significantly improved after the modification of CS-GO-APP when 15 layers of BL were applied to the wood. The LOI increased from 22 to 42 in the pure form, while the heat release rate and total heat release decreased from 105.50 kW/m^2 and 62.43 MJ/m^2 to 57.51 kW/m^2 and 34.31 MJ/m^2, respectively. Moreover, the 24-hour immersion experiments and abrasion tests proved the excellent durability of the applied coating. In addition, the SEM images of the charring residues after the flame test proved that the CS-GO-APP assembly coating can promote the formation of a charring layer on the surface of the wood. And also block the spread of flame, thus protecting the wood from fire. However, nothing is said about the environmental friendliness of these products.

Thus, from the literature [1, 2, 5, 7, 8] it is established that gypsum-based biocomposites are able to provide resistance to the effects of temperature and humidity fluctuations during operation, but the parameters that ensure their resistance to thermal effects are not determined. All this gives grounds to argue that it is advisable to conduct a study aimed at establishing parameters for the formation of biocomposites based on a hybrid binder and the influence of the components that make up their composition, as well as their role in ensuring stability.

3. The aim and objectives of the study

The aim of our work is to determine the regularities of the formation of the properties of fire-resistant biocomposites from wood sawdust and a mixture of gypsum and intumescent coating based on polyvinyl acetate dispersion (PVA dispersion) for building structures. This would make it possible to expand the scope of application of biocomposites in the design of building structures.

To achieve the goal, the following tasks were set:

– to investigate the fire-resistant properties of biocomposites from wood sawdust and a mixture of gypsum and intumescent coating based on PVA dispersion;

– to determine the features of wetting and moisture absorption of biocomposites when changing temperature and humidity fluctuations of the environment.

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 the properties of fire-resistant biocomposites from wood sawdust and a mixture of gypsum and intumescent coating based on PVA dispersion. The scientific hypothesis is the possibility of establishing the fire resistance of the biocomposite during interaction with a high-temperature flame and determining the resistance to moisture absorption when changing temperature and humidity fields.

In the process of the study, it was assumed that the process of forming the properties of fire-resistant biocomposites from wood sawdust and a mixture of gypsum and intumescent coating based on PVA dispersion is constant under the influence of external conditions. It was simplified that the temperature, humidity, and pressure of the process of forming a biocomposite on a hybrid binder do not change.

4. 2. Test materials used in the experiment

Samples of a biocomposite made of wood sawdust and a mixture of gypsum and intumescent coating based on PVA dispersion were prepared by molding in a plastic mold measuring 130 × 84 × 12 mm. Sawdust previously produced from sawmill production dried to a moisture content of 10% was used to form the plates. An intumescent coating based on PVA dispersion was used as a binder, which was diluted with water and gypsum binder was added.

The wood sawdust and binder were mixed in a container until the sawdust was 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 60 ÷ 65%.

Biocomposites were prepared with the following ratios of mass parts of filler and binder and water (Fig. 1):

1) wood chips – gypsum binder in a ratio of 1:4 and water;

2) wood chips – gypsum binder – intumescent coating based on PVA dispersion in a ratio of 1:1:1.67 and water.

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

– based on wood sawdust and gypsum binder – 133 × 83 and 14 mm thick, density 513 kg/m^3;

– from wood sawdust and a mixture of gypsum and intumescent coating based on PVA dispersion – 130 × 80 and 12 mm thick, density 320 kg/m^3.

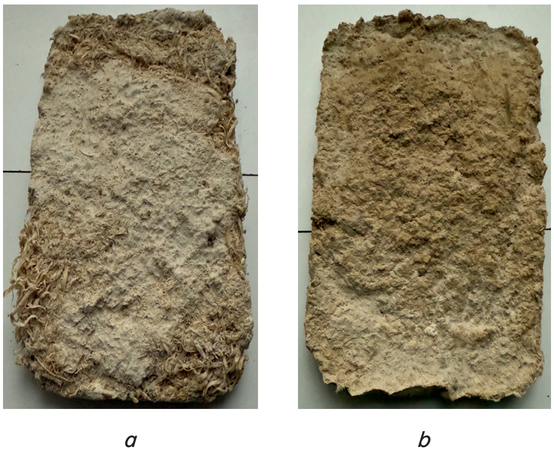


Fig. 1. Model samples of biocomposite: *a* – based on wood sawdust and gypsum binder; *b* – made of wood sawdust and a mixture of gypsum and intumescent coating based on PVA dispersion

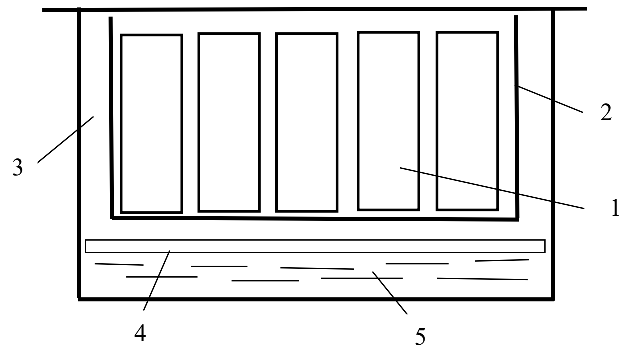


Fig. 2. Desiccator for testing moisture absorption by biocomposite: 1 – samples; 2 – cassette; 3 – desiccator; 4 – filter paper; 5 – aqueous soda solution

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

Studies on determining the thermal resistance of a fire-resistant material were carried out using a methodology that involved exposing the sample to a radiation panel and igniting it. At the same time, measurements were made of the temperature of the 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 burnt part of the sample. The flammability index was calculated using the data obtained in [13].

The study of the wetting process, which occurs as a result of the interaction of water molecules with biocomposite molecules, was carried out by applying a liquid to the surface of the biocomposite and determining the wetting angle [14]. The essence of the method is that a drop of liquid is applied to the surface of the material, and the wetting angle is determined through a microscope, and a group of solids is determined from its value. Two types of liquids are used for this purpose – polar and non-polar. Depending on the angle formed by the liquid on the material, hydrophilic (oleophobic) materials are distinguished, which are better wetted by water than by non-polar hydrocarbons, and hydrophobic (oleophilic) materials, which are better wetted by non-polar liquids than by water.

Moisture absorption is defined as the change in mass during the exposure of the material in a humid environment for a certain time. The essence of the method is that the biocomposite samples were placed in a desiccator (Fig. 2) with a saturated soda solution, which was impregnated with filter paper to increase the humidity of the environment.

The study involved periodic weighing of the biocomposite at set times, namely after 2, 3, 6, 9, 13, 21, 26 days from the moment of placement in the desiccator. To establish the operational properties of the biocomposite, the compressive strength was determined according to ISO 13061-3:2014 and evaluated according to [15].

5. Results of determining the properties of biocomposites from wood sawdust and a mixture of gypsum and intumescent coating

5. 1. Experimental studies on the thermal stability of biocomposites under the influence of high-temperature flame

Fig. 3, 4 show the process of ignition and flame propagation by a biocomposite.

Studies have shown (Fig. 3, 4) that biocomposites are low-flammable materials since no burning or smoldering was recorded during temperature exposure.

The results of 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. 5.

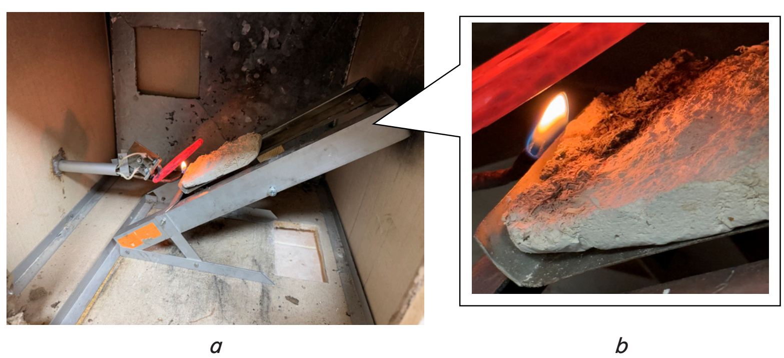


Fig. 3. Test results of the ignition process and flame spread of a gypsum-based biocomposite: *a* – test sample; *b* – burning of the sample

Fig. 4. Results of tests of the ignition process and flame propagation of a biocomposite on a hybrid binder: *a* – thermal effect on the sample; *b* – charring of the sample

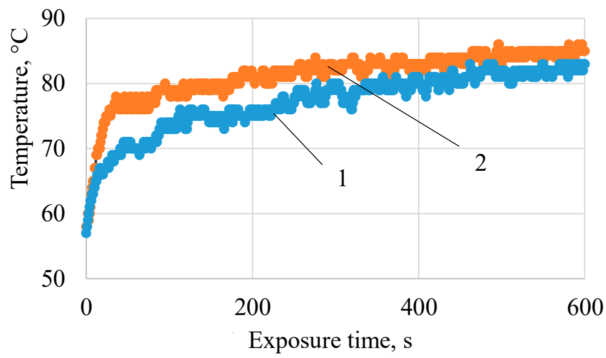


Fig. 5. Dynamics of the increase in flue gas temperature during biocomposite tests: 1 – on gypsum binder; 2 – on binder from a mixture of gypsum and intumescent coating based on PVA dispersion

During thermal action on samples of biocomposites formed on gypsum binder, the temperature of flue gases did not exceed 80°C and no ignition occurred. During the action of the radiation panel on the biocomposite formed on a binder from a mixture of gypsum and an intumescent coating based on PVA dispersion, no ignition occurred, the maximum temperature of flue gases was about 84°C. Thus, when using a gypsum binder, a non-combustible structure was formed on the surface of the biocomposite, which prevented the ignition of the sample. However, for a biocomposite on a binder from a mixture of gypsum and an intumescent coating based on PVA dispersion, the formation of charring of the surface of the sample is characteristic, which prevents its ignition.

5. 2. Results of determining the process of wetting and moisture absorption of biocomposites

Fig. 6 illustrates a study of the wetting process of the biocomposite. Fig. 7, 8 show the results of determining the contact angle of the biocomposite.

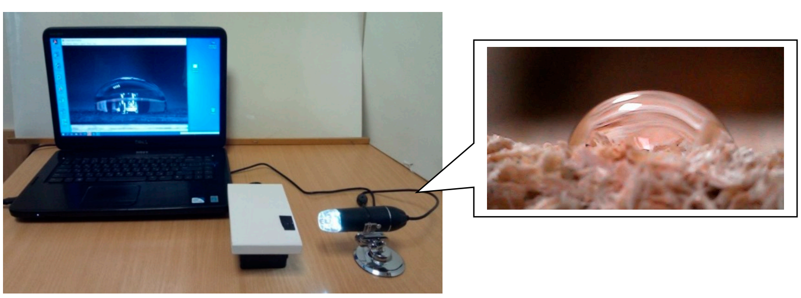
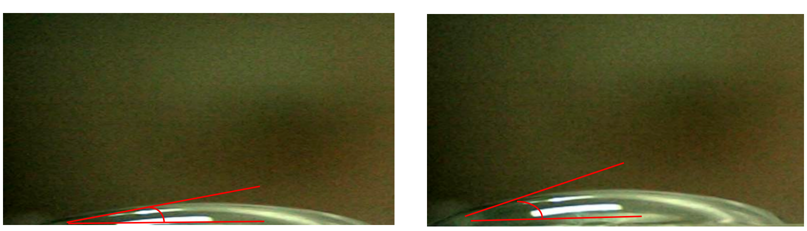


Fig. 6. Research on the wetting process of a biocomposite



a *b*

Fig. 7. A drop of liquid on a biocomposite made of sawdust and gypsum binder: *a* – water; *b* – ethylene glycol

The above results (Fig. 7, 8) show that for a biocomposite based on a gypsum binder, water and ethylene glycol create an acute droplet angle upon wetting, namely for water ~9°, and for ethylene glycol ~20°. In contrast, for a biocomposite based on a binder made from a mixture of gypsum and an intumescent coating based on PVA dispersion, water creates an acute wetting angle of ~40°, and for ethylene glycol, an angle of ~65° of the droplet upon wetting. The obtained solids belong to hydrophilic materials that have high wettability with water.

Taking into account the above research results, tests were carried out on moisture absorption by biocomposites, which are shown in Fig. 9.

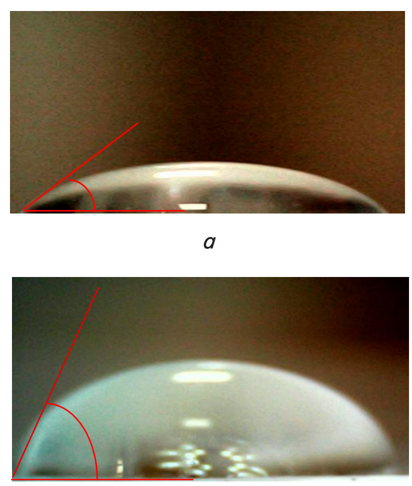
The results of experiments on water absorption of biocomposites show (Fig. 9) that the maximum mass gain of the biocomposite on a gypsum binder under the influence of moisture was almost 27% and the main increase in moisture occurred in the first 5 days of exposure. The mass gain of the biocomposite samples on a binder from a mixture of gypsum and intumescent coating based on PVA dispersion was less than 10% due to the formation of a shell on the surface of sawdust, which prevented water absorption.

The most important for the operation of the biocomposite are such physical and mechanical properties as the compressive strength limit. In this regard, the compressive strength was determined (Table 1).

Table 1

Biocomposite compressive strength value

Biocomposite	Width, mm	Height, mm	Maximum tension, N	Tensile strength, MPa	Deformation, mm
On gypsum binder	22.01	24.92	202.54	0.41	2.5
On a binder made from a mixture of gypsum and intumescent coating	25.02	23.24	1182.33	1.88	8.3



a

b

Fig. 8. A drop of liquid on a biocomposite made of sawdust and a binder on a mixture of gypsum and intumescent coating based on PVA dispersion: *a* – water; *b* – ethylene glycol

The compressive strength of biocomposites showed that the sample formed on a gypsum binder is significantly brittle and corresponds to an average value of 0.41 MPa. However, for a biocomposite formed on a binder from a mixture of gypsum and intumescent coating, the ultimate strength is 1.88 MPa, which is provided by the adhesive properties of the intumescent coating.

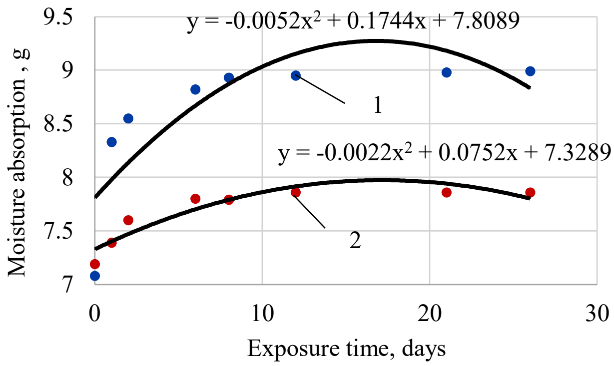


Fig. 9. Dependence of moisture absorption of biocomposites on exposure time: 1 — on gypsum binder; 2 — on binder from a mixture of gypsum and intumescent coating based on PVA dispersion

6. Research into the regularities of the formation of fire-resistant biocomposites: results and summary

Comparison of experimental studies (Fig. 4–6) on establishing the combustion process of biocomposites based on gypsum binder under the action of a radiation panel showed that the temperature of gaseous combustion products increased to 80°C, the sample did not ignite, which indicates the inhibition of combustion processes. Thus, during the use of gypsum binder, a structure is formed on the surface of the biocomposite, which prevented the ignition of wood sawdust. In this sense, the interpretation of the results of determining the ignition process of a biocomposite formed on a binder from a mixture of gypsum and an intumescent coating based on PVA dispersion is also relevant. As a result of the thermal effect, the sample did not ignite, the maximum temperature of the flue gases was about 84°C. However, for a biocomposite on a binder from a mixture of gypsum and an intumescent coating based on PVA dispersion, charring of the sample surface is characteristic, which prevents its ignition. Thus, under the influence of thermal action, chemical reactions of decomposition of ammonium polyphosphate begin, which releases phosphoric acid. Which in turn induces the destruction and dehydration of pentaerythritol with the formation of a large number of hydrocarbons, and the simultaneous decomposition of melamine leads to the release of non-combustible gases that inhibit the flame. This justifies the mechanism of operation of the intumescent coating, which is possible to identify by high-temperature exposure [16, 17].

According to the results of our study on the wetting process of the samples, it was found that for the biocomposite on the gypsum binder, water and ethylene glycol create an acute drop angle during wetting, namely for water ~9°, and for ethylene glycol ~20°. In contrast, for a biocomposite based on a binder of gypsum and an intumescent coating based on PVA dispersion, water creates an acute wetting angle of ~40°, and ethylene glycol creates an angle of ~65° of the drop when wetting (Fig. 8). The resulting solids are hydrophilic materials with high water wettability.

Analysis of the results of experiments on water absorption of biocomposites reveals that the maximum mass gain of the biocomposite on a gypsum binder under the influence of moisture was almost 27% and the main increase in moisture occurred in the first 5 ÷ 6 days of exposure. The mass gain of the biocomposite samples on a binder from a mixture of gypsum and an intumescent coating based on PVA dispersion was less than 10% (Fig. 9) due to the formation of a shell on the surface of sawdust, which prevented water absorption.

Unlike the studies reported in [1, 2, 18, 19], most attention was paid to the use of reinforcing products. However, this study considers the development of biocomposites based on a hybrid binder – a mixture of gypsum and an intumescent coating based on PVA dispersion, which is quite well known on the market.

However, in contrast to the results from [20] regarding the mechanism of moisture absorption, the following can be stated:

– the main regulator of the process is not so much the formation of a significant amount of gypsum binder, which inhibits moisture absorption, since individual protective coatings are destroyed under the influence of atmospheric action;

– a significant impact on the process of protection against moisture absorption when using a mixture of gypsum and intumescent coating based on PVA dispersion is carried out in the direction of the formation on the surface of sawdust of an elastic film resistant to destruction under the influence of temperature and humidity fluctuations.

Interpretation of the obtained results on the moisture absorption of biocomposites, since the effectiveness is confirmed by the reaction to the action of moisture, reveals the possibilities of their exploitation. Therefore, the results of the research allow us to state that the possibility of using biocomposites for construction has been established, which is a certain advantage of this study.

Our results on the compressive strength of biocomposites have certain limitations since the product formed on the basis of wood sawdust and gypsum binder is fragile and requires an increase in the binder.

In addition, the resistance of the biocomposite to thermal action provides insufficient information due to the scarcity of data and limits the use of the obtained results. The disadvantages of the study include the fact that the results of the experiments, having the most complete description of the features of moisture absorption and biocomposites, are a graphical form of display. However, thanks to experimental studies, a path has been obtained that allows us to establish the role of the intumescent coating during operation. The next area of research on the development of biocomposites on a hybrid binder may include the cycle of studies on the optimization of composition components.

7. Conclusions

1. During thermal action on samples of biocomposites formed on a gypsum binder, the temperature of flue gases did not exceed 80°C and no ignition occurred. During the action of the radiation panel on the biocomposite formed on a binder from a mixture of gypsum and an intumescent coating based on PVA dispersion, no ignition occurred, the maximum temperature of flue gases was about 84°C. Thus, when using a gypsum binder, a non-combustible structure was formed on the surface of the biocomposite, which prevented the ignition of the sample. However, for a biocomposite on a binder from a mixture of gypsum and an intumescent coating based on PVA dispersion, charring of the sample surface is characteristic, which prevents its ignition.

2. According to the results of determining the process of wetting biocomposites with test liquids, it was found that for a biocomposite on a gypsum binder, water and ethylene

glycol create an acute drop angle upon wetting, namely for water ~9°, and for ethylene glycol ~20°. In contrast, for a biocomposite on a binder from a mixture of gypsum and intumescent coating based on PVA dispersion, water creates an acute wetting angle of ~40°, and for ethylene glycol an angle of ~65° of the drop upon wetting. The obtained solids belong to hydrophilic materials that have high wettability with water. Analysis of the results of experiments on water absorption of biocomposites reveals that the maximum mass gain of a biocomposite on a gypsum binder under the action of moisture was almost 27% and the main increase in moisture occurred in the first 5 days of exposure. The mass gain of biocomposite samples on a binder from a mixture of gypsum and an intumescent coating based on PVA dispersion was less than 10% due to the formation of a shell on the surface of sawdust, which prevented water absorption.

The value of the compressive strength of biocomposites showed that the sample formed on a gypsum binder is significantly brittle and corresponds to an average value of the ultimate strength of 0.41 MPa. However, for a biocomposite formed on a binder from a mixture of gypsum and an intumescent coating, the ultimate strength is 1.88 MPa, which is provided by the adhesive properties of the intumescent coating.

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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Authors’ contributions

Yuriy Tsapko: Conceptualization, Methodology (supervisor) writing – review and editing (supervisor), Formal analysis (supervisor); **Oleksiy Tsapko:** Conceptualization (assistant), Research – conducting experiments and data analysis, writing – original draft; **Oksana Berdnyk:** Research – conducting experiments and data analysis, Writing – original draft (assistant), Formal analysis; **Ruslan Likhniovsky:** Methodology (assistant), Data curation, Validation; **Vladyslav Halitsa:** Resources, Verification, Funding; **Maryna Sukhanevych:** Raising funding, Verification, Visualization; **Ruslan Klymas:** Investigation, Financing, Resources; **Vitaliy Prysiazhnyuk:** Validation, Financing, Visualization; **Pavlo Illyuchenko:** Resources, Supervision, Verification.

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