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REVEALING PATTERNS IN REDUCING THE FIRE-HAZARDOUS PROPERTIES OF INSULATION MADE FROM PLANT RAW MATERIALS

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An issue related to the use of hemp bundle insulation for building structures is to ensure their fire resistance under the action of a low-calorie ignition source. Therefore, the object of research was the change in the properties of the insulation during fire protection with its compositions capable of forming a layer of pino-coke under the influence of high temperature. On the basis of experimental data, it was established that at fire protection of insulation with a fire retardant agent, hydrolytic stable ethers containing phosphorus and nitrogen atoms are formed on the surface of the fibers. According to the temperature values and the shape of peaks on the DTA curve, it was established that at fire protection, the height of the peaks decreases and the width increases, which characterize the flow of exothermic transformations and the destruction of hemp fibers. At the same time, it was established that the formed residue has 13.3 % for impregnation and 26.6 % for coating. It has been proven that in the process of thermal action on the fire-resistant coating, the heat insulation process of the insulation consists in the formation of soot-like products on the surface of the material. So, it was determined that the sample did not catch fire, it was charred in the place of the radiation panel, and the burning was not recorded. On the other hand, for a sample of insulation treated with a coating during thermal action, the formation of a heat-insulating layer of foam coke occurred, which inhibits the penetration of heat, the temperature of flue gases did not exceed 100 °C, and the flammability index was 0. The practical significance is that the results were taken into account when designing buildings and structures. So, there are reasons to assert the possibility of targeted regulation of fire protection processes of insulation by applying coatings that form a protective layer on the surface of the material

Keywords: protective means, insulation from hemp, thermal destruction of the surface, fire protection of hemp fibers, swelling of the coating

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1. Introduction

Natural biological insulation materials have become the most interesting products due to their good properties and low carbon emissions, gaining wide recognition for their resilience to climate change and the impact of the construction industry on the environment. Hemp is a raw material both for the textile industry and a raw material used in many areas, in particular, non-woven materials, heat-insulating materials used in various industries. Hemp insulation retains heat well, does not emit harmful substances and is one of the methods of ecological insulation of buildings. Insulation is used for walls, ceilings, production of sandwich panels, frame houses, when repairing roofs, attics, walls, external and internal partitions. However, unresolved issues of fire protection of such products reduce the possibility of their use in construction. At the same time, the process of ignition and spread of burning is progressive since these materials are flammable and quickly spread flames, and the fire extinguishing methods are extremely insufficient. To reduce these disadvantages, fire-resistant treatment is carried out, which gives the insulation the ability to resist the action of flame and its spread. It is known that cellulose-containing building materials are not capable of independent flame combustion by themselves, only the products of their decomposition burn under the influence of temperature. And the introduction of flame retardants into the material reduces the amount of formation of flammable volatile products, inhibits gas-phase flame reactions, and eliminates flameless combustion of the carbonized residue.

Taking into account the peculiarities of the chemical structure and structure of heat-insulating material made of hemp at fire protection, there are difficulties in using impregnating fire retardants for wood. This is primarily due to the fact that the structure and composition of hemp fibers are different from wood and the treatment process is not achieved. One of the ways of fire protection of such a material is to apply a fire-resistant intumescent coating on its surface, which prevents heat from reaching the insulation for a certain time.

Therefore, the use of effective fire retardants is aimed at the construction of objects where the use of existing impregnation compositions is ineffective. The use of new ones requires reliable techniques for studying the properties of the fire-resistant coating. This predetermined the need for research in this area.

2. Literature review and problem statement

Study [1] describes the use of natural fibers as natural and sustainable reinforcing agents for biocomposite materials in strategic sectors, for example, the construction industry. The work evaluates the use of biomatrices in composites, demonstrating their feasibility and how they affect the properties of the final material. The proposed bio-resin increases the fire resistance and reduces the water absorption capacity of natural fibers, which allows the use of composites as a final product in the construction sector. Thus, the possibility of making a biocomposite from non-woven natural fibers was demonstrated and it was proved that biomaterials are a solution for developing sustainable products that meet user requirements. But it is not revealed how this affects the strength during operation.

A new bioclay plaster, as reported in [2], was developed by adding hemp powder to clay plaster to improve the performance of buildings by buffering indoor moisture. As well as the creation of a fire-insulating layer for encapsulation of flammable substrates on a bio-based basis and increasing the air tightness of the system by closing the seams. The results showed that the plaster composition affects the drying shrinkage, thermal conductivity, density, and moisture buffer value of the plaster. The thermal conductivity of the new bioclay plaster decreased with a decrease in the proportion of earthen clay. The amount of hemp powder had little effect on the thermal conductivity of the plaster, while the amount of hemp powder had a small effect on the moisture buffering. The new bioclay plaster demonstrated increased fire resistance. Detailed hygrothermal characterization using buffer moisture measurement and thermal conductivity analysis revealed that the new bioclay plaster showed good moisture buffering capacity. But it is not clarified for which thickness the product is intended and how it affects thermal conductivity.

Study [3] describes new hemp-based composite materials developed for use in construction as components of a multilayer structure for facilities that provide both thermal insulation and physical-mechanical stability. Composite panels were made by gluing hemp fiber with a new hybrid organic-inorganic binder. The panels were then characterized in terms of physical and microstructural properties, including bulk density, water absorption, thickness swelling, and weight loss after immersion in water, microstructural features, thermal properties (thermal conductivity), and reaction to fire. The authors also considered mechanical properties (compressive strength, bending strength, tensile strength, resistance to axial extension of screws). The panels showed promising physical, thermal, and mechanical characteristics. In addition, the advantage of new composites is a significantly low impact on the environment (due to the nature of both the dispersed and the binding phase) and the absence of a negative impact on human health. However, in general, they are not comparable to the characteristics of commercially available products.

In study [4] it is noted that insulating non-woven materials from natural raw materials can be attributed to the group of environmentally friendly materials for heat and sound insulation of buildings. The characteristic properties of light heat-insulating materials from natural raw materials in comparison with similar chemical materials are considered. The types of raw materials used for the manufacture of non-woven material insulation (wool, hemp, linen) are listed. The characteristics and coefficients of the properties of these materials that affect the microclimate of the room (hygroscopicity, ability to eliminate electrostatic charges) are given. In addition, a method of increasing the fire resistance of plant fibers (flax, hemp) by means of processing is discussed. The results of tests on flammability, thermal and acoustic properties and other biophysical tests confirming the comfort of the product are presented. However, there are no examples of areas of application of insulating non-woven material in construction.

The main objective of study [5] is to characterize a new bioinsulating material consisting of fibers and an adhesive based on corn starch. This innovative material is developed from the waste of a marine plant called *Posidonia oceanica* (PO), which is found in abundance along the coast of Algeria. Four samples with different volume fractions of glue (15 %, 20 %, 25 %, and 30 %) were prepared and tested. Key characteristics studied include density, thermal conductivity, and specific heat. The results obtained for the thermal conductivity of different composites range from 0.052 to 0.067 W/(m·K). In addition, the findings regarding thermal conductivity and specific heat are similar to those reported in the scientific literature. However, the capillary absorption of the material is slightly lower, indicating that the developed biomaterial exhibits interesting thermal characteristics, but the authors did not specify its suitability for use in insulation.

In [6], a rigid thermal insulation panel for construction applications is presented. It mainly consists of eucalyptus bark fibers (90 % by weight), as well as synthetic fibers (10 % by weight). After barking, the bark underwent mechanical processing in a hammer mill. The fibers were then fed into a variable speed fiber opening machine to evaluate the process. The mixed fibers were transported to an air system to fix the bulk density. Eucalyptus bark fibers are morphologically and mechanically characterized. The samples demonstrated thermal insulation properties with thermal conductivity values in the range of 0.038–0.04 W/(m·K). However, the panels showed low mold resistance due to the chemical composition of eucalyptus bark.

As noted in work [7], the demand for environmentally friendly materials is growing, so the advantage has become environmentally conscious architecture and the use of environmentally friendly materials. The transition from artificial materials to products made from renewable raw materials is becoming more and more relevant. The purpose of the study was to investigate the properties of the material and the possible options for using thermal insulation from a straw blanket. The results showed that it has a number of advantages that can make it competitive in the market of thermal insulation materials. However, the values of these parameters do not cover a wide range of applications.

In paper [8], an attempt was made to use cotton filter waste (CFW) collected from the humidification unit of a spinning mill as a reinforcement in the production of biocomposites with a corn starch (CS) matrix. Starch was considered the most suitable matrix because it is stable, abundant, natural, biodegradable and, more importantly, able to exhibit thermoplastic behavior at high temperatures. Sheets of cornstarch composites reinforced with different weight % of purified filter cotton waste were produced using hand layup and pressing techniques. It was established that cotton waste with a content of 50 wt. % is the optimum loading in terms of tensile strength, Young's modulus, flexural strength, viscosity, impact strength and thermal conductivity of biocomposites. SEM micrographs revealed good interfacial adhesion between the matrix and filler interfaces, with the most significant adhesion for composites containing 50 % fibers, which simultaneously improved the mechanical properties of the composites. However, for insulating properties, a key role is played by their stability under the strong influence of fire.

In [9], significant efforts were made to develop thermal insulation materials with better characteristics than existing products. Cellulose and wheat straw were characterized in this study. Then they were mixed in different proportions and densities and the best thermal properties were selected. The materials were chemically analyzed using TAPPI 2007, thermogravimetric and infrared spectroscopy along with their thermal conductivity measurements using a thermal property analyzer based on the transition line heat source method. The results show that both types of raw materials are similar to each other in terms of chemical composition. In the mixed form, they have a thermal conductivity of 0.031 to 0.036 W/(m·K), which is comparable to several conventional heat insulators. But it has not been established how this affects their stability during operation.

The experimental work reported in [10] contributes to the study of sustainable integrated solutions based on a solution reinforced with jute fibers to obtain an optimal balance between the mechanical behavior and thermal properties of the studied system. To achieve this, raw jute fiber of different percentages (0.5 %, 1 %, 15 %, and 2 %) and lengths (5 mm, 10 mm, and 30 mm) were used as a reinforcing agent for the composite mortar. As fiber is gradually introduced and the percentage increases, the mechanical properties (compressive strength and flexural strength) deteriorate, while the insulating capacity improves almost linearly compared to the conventional samples without fiber. The presence of longer fibers in the sample showed better bonding ability and higher energy capacity, that is, the presence of jute fiber improved the energy absorption capacity of the composite samples. In contrast to the insulating capacity, the 5 mm fiber has a lower thermal conductivity compared to the 10 and 30 mm fibers. But nothing is said about the cost of production.

The purpose of work [11] was a detailed analysis for the thermal characteristics of recycled materials for building insulation. For this purpose, the thermal behavior of various materials representing industrial residues or waste, collected or processed using available local raw materials, was investigated. These include plaster with recycled materials; plasters with natural fibers; building insulating materials from natural fibers. The results show that the studied materials improved not only the energy performance but also improved environmental comfort in both new and existing buildings. In particular, plasters and mortars with recycled materials and with natural fibers showed, respectively, thermal conductivity values (at 20 °C) lower than 0.475 and 0.272 W/(m·K). Whereas natural fiber building materials were always less than 0.162 W/(m·K) with lower values for recycled materials compounds (0.107 W/(m·K)). However, nothing is said about the range of their application.

Study [12] attempted to develop paints to minimize damage in case of fire, which can block flames and control the spread of smoke and have additional sound insulation and waterproofing functions. The highly elastic paint was produced by mixing a flame retardant polyurethane dispersion (PUD) with an acrylic emulsion binder and adding different mass fractions of expanded graphite (EG). The thermal, physical, and morphological properties of the finished paint were analyzed. The thermal properties of the mixed paint were analyzed and intended to be used as input data (heat transfer coefficient, specific heat) for fire simulation. The raw data were used to predict how much the temperature would change depending on the time of fire since the fire resistance of paints can be predicted without determining the fire protection effectiveness. Two hours after the fire broke out in the virtual space, it was found that when the mixed paint was applied, the ambient temperature in the penetration zone was lower than when no mixed paint was applied. However, it was not possible to establish the flammability limits for these products.

Paper [13] examines an approach to passive fire protection based on thermal insulation using intumescent materials and fire blankets for reliable accident resistance. Work puffs and fire blankets can block a significant portion (typically 60 to 90 %) of incident heat. Impact-resistant, high-strength fabrics in both soft and hard forms can also be used as parts of a multi-layer protective assembly. However, optimal decisions regarding its concentration have not been determined.

A new composite foam from bio sources has been successfully tested for fire-retardant properties [14]. This material, which has similar thermal insulation properties and density to flame retardant polyurethane foam (FR-PUF), shows promising improved fire resistance properties as assessed by various methods such as thermogravimetric analysis (TGA), pyrolysis combustion flow calorimetry (PCFC). Pyrolysis methods confirm the properties of this alternative material in terms of fire protection (pHRR, THR, EHC, time to ignition, flame duration or residue formation), especially for a heat flux not exceeding 50 kW/m^2. At higher heat flux (i.e., 75 kW/m^2), the flame retardant properties tend to decrease, but remain at a higher level than FR-PUF. A study of the effect of AF thickness shows that the critical thickness (CT) is close to 1.5–1.7 cm: heat diffusion and material combustion are limited by the CT layer, which protects the lower layers from burning. Many factors can explain this behavior, for example low thermal conductivity, low heat of combustion, formation of carbonization and release of water from the lower layers. That dilutes the gases that are released during the burning of the surface layers and contributes to the extinguishing of the flame. However, nothing is said about the impact on the ecosystem.

Thus, it was established from the literature [1–14] that ecologically safe insulators made of renewable plant materials are becoming widely used. However, for such a material as hemp insulation, there are no data on its fire-resistant treatment, the value of which is necessary for the design and manufacture of heat-insulating products since it has specific properties and forms of application. Therefore, establishing the parameters of fire protection of structures made of insulation based on hemp and the effect of coatings on the process of thermal destruction predetermined the need for research in this area.

3. The aim and objectives of the study

The purpose of our work is to identify the patterns of suppression of the process of thermal destruction of fire-resistant insulation from hemp bundle under thermal action. This makes it possible to substantiate protective coatings on objects with the use of insulation based on plant raw materials.

To achieve the goal, the following tasks were solved:

– to conduct a study of changes in the structure and features of the destructive processes of fire-resistant insulation treated with an impregnating composition and a swelling coating;

– to establish changes in the flammability index under temperature influence on a sample of treated insulation depending on the nature of the flame retardant.

4. The study materials and methods

4. 1. The object and hypothesis of the study

The object of our study is heat-resistant properties of a fire-resistant insulation sample.

The scientific hypothesis assumes reducing the indicators of thermal destruction of insulation from a hemp bundle when it is fireproofed by both impregnation and coating.

In the research process, the following assumptions and simplifications were adopted, which relate to the peculiarities of heat exchange and other processes at the modeling object:

– those determining the impact of changes in external conditions on the object of research and the lack of interrelationships between process implementations, namely: the flow of heat exchange processes in the insulation are the same, temperature, humidity, and pressure are not variable;

– the insulation sample is homogeneous.

4. 2. Researched materials used in the experiment

To determine the thermal resistance of fire-resistant insulation samples, we used construction insulation KONSULATE® from hemp bundle produced by TM KONSULATE by Sumykamvol, size 320×140 mm, thickness 15 mm, density 62...67 g/m^3 (Fig. 1). For fire protection of the insulation, fireproof impregnation agent “FIREWOL-ATTIK” (Ukraine) was applied onto the surface with a consumption of 300 g/m^2 and intumescent coating “FAIRWOL-WOOD” (Ukraine) with a consumption of 250 g/m^2.

Fig. 1. Hemp insulation

After drying to a constant mass of fire-resistant insulation, tests were carried out for the effectiveness of fire protection.

4. 3. Methods for researching the structure and properties of fire-resistant hemp insulation

Establishing patterns of changes in the structure during fire protection of insulation was carried out by means of Fourier transform infrared spectroscopy (FTIR) and identification by thermogravimetric analysis.

Research on determining the thermal stability of fire-resistant insulation was carried out according to the methodology, the essence of which was the impact on a sample of a radiation panel and its ignition. With the subsequent measurement of the temperature of the combustion products and the time of its achievement, the time of ignition and passage of the flame front of the surface areas, the length of the burnt part of the sample. Based on the obtained data, the flammability index was calculated [15].

Fourier transform infrared spectroscopy (FTIR) was performed taking into account [16]. Research method: 0.5 mg of the sample, crushed from 70 mg of potassium bromide (cleaved from a single crystal). From the resulting mixture, the tablet was compressed under a pressure of 10 MPa, achieving maximum optical transparency (to reduce scattering). The spectrum was recorded in the range of 4000–400 cm^{-1}, with an optical slit width of 4 cm^{-1}, the spectrum was averaged over 12 scans. The analysis was performed on a Spectrometer Spectrum One (Perkin Elmer) (USA).

Thermogravimetric analysis was performed according to [17]. In order to determine the range of temperatures at which the thermal destruction of wood occurs most intensively, a thermogravimetric study of destruction processes was conducted under a dynamic mode. For this purpose, equipment was used employing a scientific research station by the company TA (thermal analysis) Instruments (USA) with a TGA (thermogravimetric analysis) module – TGA Q50.

5. Results of studying the fire-resistant properties of hemp insulation and its structure

5. 1. Results of studying changes in the structure of hemp insulation at fire protection

Fig. 2 shows the IR spectra of the studied samples. Hemp fibers consist of cellulose, lignin, and hemicelluloses, so the description of the IR spectra of flame-retardant hemp samples is given taking into account the absorption bands of cellulose, lignin, and hemicelluloses (4-O-methyl-glucuronoxylan).

For all plants and materials from them, the main transmission range of interest lies within 2500–3700 cm^{-1}.

For lignin contained in untreated hemp fibers, the region of the IR spectrum of 3700–3100 cm^{-1} characterizes the valence vibrations of different types of hydroxyl groups. All hydroxyl groups of lignin are involved in hydrogen bonds.

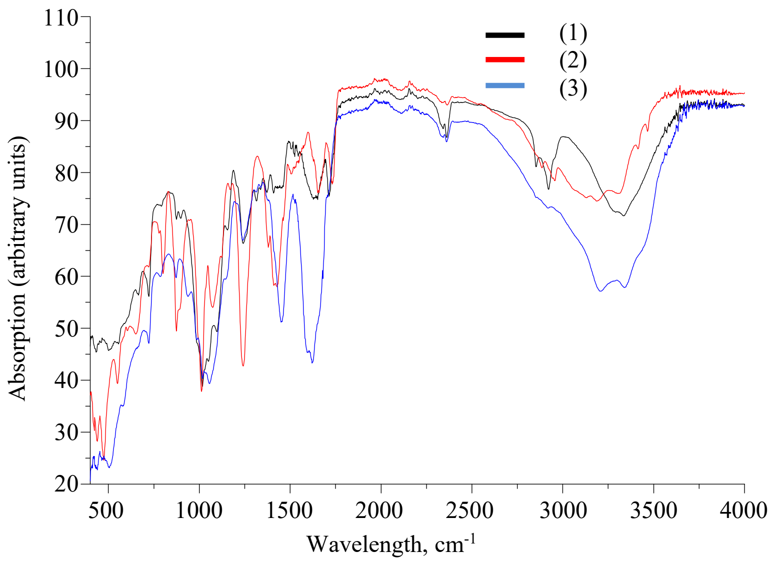


Fig. 2. Absorption spectra of hemp insulation samples: 1 — untreated; 2 — impregnated with fire retardant; 3 — covered with a swelling coating

In the region of 3000–2800 cm^{-1} are the bands of valence vibrations of C–H bonds. In general, valence vibrations of aromatic C–H bonds have absorption or transmission bands in the region of 3100–3000 cm^{-1}, but in the spectrum of lignin, a wide band of valence vibrations of OH groups involved in hydrogen bonds is superimposed on this region. The region 3000–2800 cm^{-1} characterizes symmetric and asymmetric C–H valence vibrations in methyl and methylene groups. The following vibrations are distinguished: the bands at 2980–2970 cm^{-1} and 2950–2930 cm^{-1} are caused by asymmetric, and the maximum at 2860–2850 cm^{-1} by symmetric valence vibrations of C–H bonds in methyl groups.

The IR spectrum of hemp cellulose is superimposed on the spectrum of lignin. In the region of 3700–3100 cm^{-1}, valence vibrations of hydroxyl groups are manifested. All hydroxyl groups of cellulose are involved in hydrogen bonds.

Valence fluctuations of C–H bonds in methylene and methyl groups of cellulose are manifested in the region of 3000–2800 cm^{-1}. Bands at 2945 and 2853 cm^{-1} characterize asymmetric and symmetric valence vibrations of methylene groups, respectively. Four of the five C–H valence vibrations appear at 2914, 2897, 2870 cm^{-1}, and 2970 cm^{-1}.

The spectra of hemicellulose are also superimposed on the spectra of lignin and cellulose. For example, in the spectrum of xylan, the region of 3700–3100 cm^{-1} appears weaker than that of cellulose and lignin.

Hydroxyl groups included in the intramolecular H-bond have an absorption (transmission) band in the range of 3570–3450 cm^{-1}, in the intermolecular bond – in the region of 3460–3100 cm^{-1}. The free OH group appears in the interval 3700–3500 cm^{-1}.

The bands near 2975, 2957, 2914, and 2873 cm^{-1} probably relate to valence vibrations of C–H groups. The band at 2935 cm^{-1} characterizes the asymmetric oscillation of CH_2. A separate band ~2853 cm^{-1} characterizes the symmetric valence vibration of the methylene group.

The presence of chemical interaction with cellulose is indicated by an increase in the optical density of the absorption bands: the peak at 1100 cm^{-1}, corresponding to valence vibrations of the glycosidic bond in the cellulose macromolecule. And also, the absorption bands of 1370 cm^{1}, which characterize the valence vibrations of the ether bond and the deformation vibrations of O–H groups. And the peak at 2900 cm^{-1}, which is responsible for valence vibrations of C–H bonds present in cellulose molecules.

Thermogravimetric analysis was performed to identify the individual characteristics of the impregnation and coating of the insulation from the hemp bundle. Graphic images of thermogravimetric analysis of samples are shown in Fig. 3, 4.

Analysis of our TGA results for samples of fire-resistant heat-insulating material made of hemp (Fig. 3, 4) reveals that from the beginning of heating (20 °C) to 100 °C, the TG curves reflect the loss of unbound water by the samples, the main amount of which is released in the range of 40–50 °C (DTG curves).

Further, on the TG and DTG curves from 100 °C to 200 °C, a slow decomposition of the components of the flame retardant material, as well as hemp, in particular, less stable hemicelluloses, is observed. After 200 °C and up to approximately 400 °C, the TG curves show a sharp increase in destructive processes in the fire-resistant material. At the same time, the maximum mass loss of the samples was recorded at a temperature of about 230 °C for impregnation and 400 °C for coating. And also, the formation of coke residue, which burns out at temperatures above 400 °C.

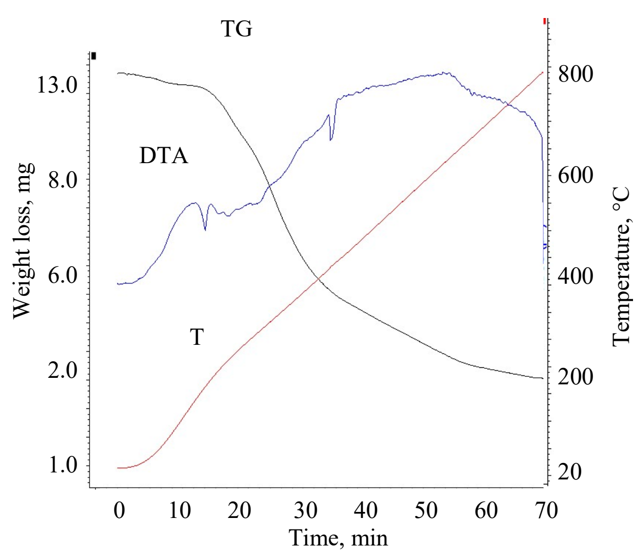


Fig. 3. Curves of thermogravimetric analysis for samples of fire-resistant insulation treated with a coating: T — temperature curve; TG — mass loss curve depending on temperature increase; DTA — thermal effects curve

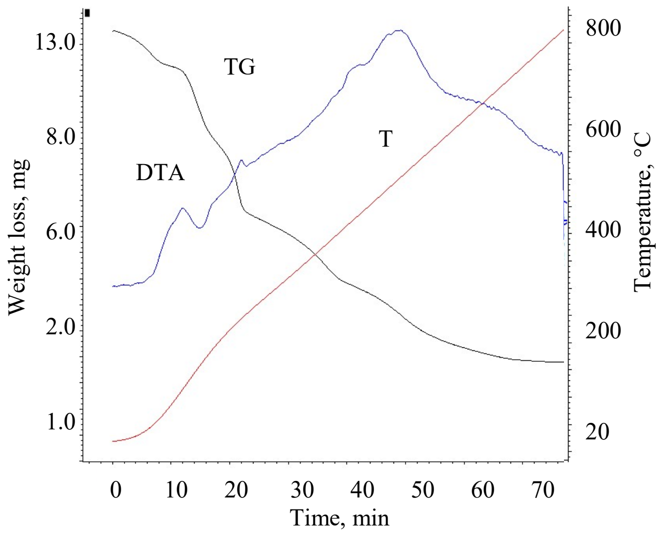


Fig. 4. Curves of thermogravimetric analysis for samples of fire-resistant insulation treated by impregnation: T – temperature curve; TG – mass loss curve depending on temperature increase; DTA – thermal effects curve

Combustion of coke residue is characterized by peaks and shapes of peaks on the DTA curve that differ in terms of temperature values. Namely, the height decreases and the width of the peaks that characterize the flow of exothermic transformations increases, as a result of which the end of the thermo-oxidative destruction process is fixed at higher temperatures. These features indicate a different qualitative (N/C ratio) and quantitative chemical composition of the coke residue, namely polyaromatic hydrocarbons. Upon reaching 800 °C, unburned samples have residues of inorganic nature, in particular, the coated material has a residue of 13.3 %, and the coated material has a residue of 26.6 %, respectively.

5. 2. Results of determining the thermal resistance of hemp insulation when treated with impregnation and coating

Fig. 5–7 show the process of ignition and spread of flame by insulation.

a *b*

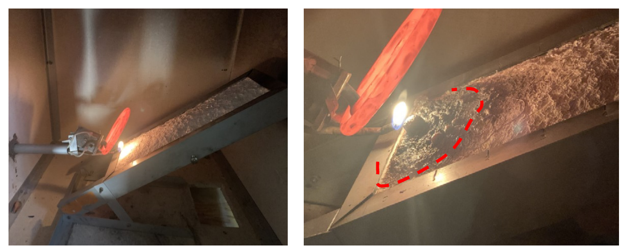
Fig. 5. Results of studies into the process of ignition and spread of the flame by the insulation: *a* – the effect of the flame on the sample; *b* – burning of the material

The results of studies on determining the increase in the maximum temperature of gaseous combustion products (Dt, °C) of the insulation, carried out under laboratory conditions, are shown in Fig. 8, and given in Table 1.

Our studies have shown (Fig. 8) that the insulation made of hemp is a flammable material, since, during the action of the flame, the sample instantly ignited, which led to its combustion

a *b*

Fig. 6. Results of studies into the process of ignition and flame propagation by insulation treated with impregnation: *a* – the effect of the flame on the sample; *b* – charring of the material



a *b*

Fig. 7. Results of studies into the process of ignition and flame propagation by insulation with a treated coating: *a* – the effect of the flame on the sample; *b* – swelling of the coating (highlighted area)

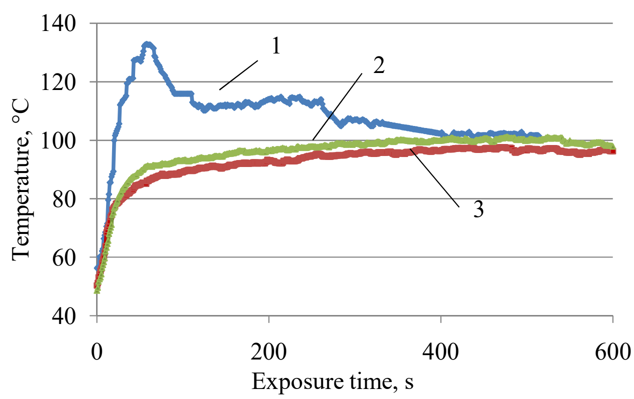


Fig. 8. The dynamics of flue gas temperature rise during insulation tests: 1 – untreated sample; 2 – sample treated by impregnation; 3 – the sample is coated

When the radiation panel acted on an untreated sample of insulation (curve 1, Fig. 5), the sample ignited for 6 seconds, which led to an increase in the temperature of gaseous combustion products to 133 °C and its combustion. During the tests of a sample of insulation fireproofed by impregnation, it was established that the sample did not catch fire, it was charred in the place of action of the radiation panel, and no burning was recorded. On the other hand, for a sample of insulation treated with a coating, under the influence of high temperature of the radiation panel, the coating swelled with the formation of a heat-insulating layer of coke foam. That did not allow the material to burn; the temperature of the flue gases did not exceed 100 °C, and the flammability index was 0 (Table 5).

Table 1

The time of passage of the control points by the flame front

Sample of hemp insulation	Flue gas temperature, °C		Ignition time, s	Time of passage of the sample sections along the flame front, s									Time to reach maximum temperature of flue gases, s	Sample burning length, mm	Flammability index
	T_1	T_{max}		1	2	3	4	5	6	7	8	9			
Raw	56.3	133	6	12	17	16	8	4	4	3	3	2	58	300	39.6
Treated by impregnation	50.4	96.3	–	–	–	–	–	–	–	–	–	–	600	0	0
Treated with coating	48.6	97.9	–	–	–	–	–	–	–	–	–	–	600	0	0

6. Discussion of results related to determining the effectiveness of reed fire protection

When the flammability of insulation from a hemp bundle was investigated, as indicated by the research results (Fig. 5, 8, Table 1), when the ignition source acts, there is instantaneous ignition and rapid spread of the flame over the surface. On the other hand, for a fire-resistant sample of insulation treated with impregnation, due to the action of flame retardants, the processes of ignition and flame spread are significantly slowed down (Fig. 6–8, Table 1). This mechanism of the protective agent is caused primarily by the decomposition of flame retardants under the influence of temperature with the absorption of heat and the release of non-combustible gases, the change in the direction of the decomposition of the material in the direction of the formation of a non-flammable coke residue. Under the influence of thermal action on the surface of the insulation with a fire-resistant coating, a swollen layer of pinocoke is formed, which slows down the processes of heat transfer to the flammable material and its ignition.

It should be noted that the penetration of the impregnation composition into the hemp fiber structure does not create a rigid material, and the presence of a swelling coating leads to the formation of an elastic film on the surface of the insulation resistant to vibrations. Obviously, this mechanism of influence of the elastic film is the factor regulating the process, thanks to which the fire resistance of the insulation is preserved. In this sense, there is an interpretation of the results of determining the flammability of fire-resistant insulation after exposure to flame, namely the charring of the material and the formation of a layer of pinocoke under thermal influence. The temperature of flue gases during thermal action on the sample was at least 98 °C. This indicates the formation of a temperature barrier, which can be identified by the method of thermal impact on the samples [18, 19].

This means that taking this fact into account opens the possibility for effective regulation of the properties of fire-resistant insulation directly under the conditions of industrial production.

This does not differ from the practical data well known from works [12–14], the authors of which associate the effectiveness of fire protection with the process of inhibiting oxidation in the gas and condensed phases. And also, with the formation on the surface of the organic material of a heat-protective layer of pinocoke under the influence of the radiation panel. But, in contrast to the results of research reported in [20, 21], the obtained data on the influence of flame retardants and intumescent coating on the process of inhibition of temperature transfer allow us to state the following:

– the main regulator of the process is not so much the formation of significant amounts of flame-inhibiting gases since individual fire-resistant coatings are destroyed under the influence of high temperature;

– a significant influence on the process of fabric protection when applying a fire-resistant coating is carried out in the direction of the formation of a layer of foam coke from an elastic film on the surface of the insulation resistant to destruction under the influence of product vibrations.

Such conclusions can be considered appropriate from a practical point of view because they allow a reasonable approach to determining the required amount of fire retardant. From a theoretical point of view, this allows us to assert the determination of the mechanism of temperature inhibition processes, which is a certain advantage of this study.

However, it is impossible not to note that the results of determining the flammability of fire-resistant insulation indicate an ambiguous effect of flame retardants on changes in fire-resistant efficiency [22]. This is manifested, first of all, in the temperature of the flue gases during the burning of the sample and the spread of the flame over the surface, and in general, the determination of the flammability index during the tests of the fire-resistant insulation. Such uncertainty imposes certain restrictions on the use of our results, which can be interpreted as the shortcomings of this study. The disadvantage of the formed curtain for burning is the high temperature, which must be reduced much lower than the decomposition temperature of the plant material. The impossibility of removing the limitations within the framework of this study gives rise to potentially interesting areas of further research. They, in particular, may focus on detecting the moment of time, from which the fall of fire-resistant properties begins to protect the insulation under the influence of high temperature. Such detection will allow us to investigate the structural transformations in the insulation material, which begin to occur at this time, and to determine the input variable parameters of the process, which significantly affect the beginning of such a transformation.

7. Conclusions

1. On the basis of experimental data, it was established that at fire protection of hemp insulation with an impregnating composition, hydrolytic stable ethers containing phosphorus and nitrogen atoms are formed on the surface of the fibers. At the same time, there is no noticeable destruction of intramolecular bonds, the orderliness of the fibers increases. The impregnation composition interacts with the hydroxyl groups of cellulose, located near the glucopyranose

ring, and with the carboxyl groups of lignin. When the surface of the hemp fiber is treated with a coating, the intensity of the peaks in the frequency of the aromatic C–H bonds significantly exceeds the intensity of the same peaks in the untreated fiber, which indicates the grafting of phosphorus-ammonium compounds into the cellulose.

Thermogravimetric analysis data show the processes of water loss and decomposition of hemicellulose, cellulose, and lignin, as well as burning of coke residue. Heating in the range from 40 to 150 °C contributes to the drying of the insulation, when operating from 150 to 450 °C, a sharp increase in destructive processes is observed. The burning of the coke residue is characterized by peaks with different temperature values and the shape of the peaks on the DTA curve, namely, the height decreases and the width of the peaks, which characterize the flow of exothermic transformations, increases. As a result, the end of the thermo-oxidative destruction process is recorded at higher temperatures. When reaching 800 °C, the remains of an inorganic nature were obtained that did not burn, in particular, the material treated by impregnation has a residue of 13.3 %, and treated with a coating – 26.6 %, respectively.

2. When the radiation panel acted on a sample of insulation fireproofed with an impregnating composition, it was established that the sample did not catch fire, it was charred in the place of the radiation panel, and no burning was recorded. On the other hand, for a sample of insulation treated with a coating during exposure to high temperature, the coating swelled with the formation of a heat-insulating layer of foam coke. The formed foam coke inhibits the penetration of heat; the temperature of the flue gases did not exceed 100 °C, and the flammability index was 0.

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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