The flammability of wood largely limits the use of wooden structures in modern construction. Therefore, there is a need to protect the wooden structures of buildings and structures from fire danger.

Ammophos-A, ammonium sulfate, expanded perlite6 and epoxy were used to develop the fire-retardant surface coating. The experiments were carried out by changing the amount of one of these components in the composition, leaving the others constant. At the same time, fire hazard indicators were controlled parameters. In this way, the optimal ratios of the components of the flame-retardant composition were established, which were: 15:15:10:50 (wt.%), respectively, ammophos-A, ammonium sulfate, expanded perlite, epoxy resin, further designated flame retardant AS-143. The test parameters of structural samples treated with this flame retardant at a consumption of 400–500 g/m^2 were: weight loss 4.0–5.0 %, flame burning time 11–18 s, flameless 19–23 s. The effectiveness of the flame retardant AS-143 was established in comparison with flame retardant No. 13, which, according to the weight loss of the samples, was 43.2 %.

The essence of the results is explained by the correct selection of chemical compounds and their component ratio in the fire-retardant composition, which exhibit a synergistic character during the combustion of wooden structures.

At the next stage, in addition to surface treatment of wooden structures, they were faced with fire-resistant plasterboard sheets. Fire tests were carried out under field conditions for 30 minutes, the results of which were: the length of flame propagation over the surface of the samples was 456–678 mm; flame propagation speed 0.015–0.023 m/min.

The data indicate that wooden structures treated in a combined way belong to group I of fire protection efficiency. These structures can be safely used in buildings and structures, especially with enclosing, attic, or attic types

Keywords: wooden structures, fire, components, fire-protection, coating, mass loss, flame combustion, flame retardant, synergism

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IMPROVING THE FIRE RESISTANCE OF WOODEN STRUCTURES BY A COMBINED METHOD

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1. Introduction

Wood played an irreplaceable role in the development of human civilization, as it was used as building, fuel material, and for other economic purposes. The widespread use of wood at all times was due to its number of positive properties: high strength, environmental friendliness, ease of processing, etc. [1]. One of the main disadvantages of wood is its flammability, according to the classification of which it belongs to the group of combustible materials. This circumstance largely limits its use in modern construction. Every year in Azerbaijan, hundreds of fires are recorded in buildings and structures for various purposes, accompanied by heavy losses, including human ones [2].

Carrying out special fire prevention measures is an urgent task of modern construction industry. The cost of these measures is up to 10 % of the total cost of structures and up to 30 % of the cost of structures subject to fire protection [3]. In modern construction, combustible elements include structures and products with a polymer base, including wood. Therefore, there is a need to protect wooden structures of buildings and structures from fire hazard. Especially, much attention is paid to ensuring the fire safety of load-bearing wooden structures, buildings, and structures with enclosing, attic, or mansard types.

In modern construction, wooden structures are subjected to structural and chemical fire protection. The effectiveness of fire protection of wood by constructive methods is determined, first of all, by the resistance to fire and the heat-insulating ability of fire-retardant plate and roll materials and other means. It has been established that the structural method of fire protection of wood is mainly effective only with a large thickness of materials. On the other hand, this method of fire protection is laborious and economically unprofitable because of high cost [4].

For wooden structures of buildings and facilities, chemical methods of fire protection are widely used. They are varied and include a wide range of impregnating and coating compounds with high resistance to fire and high temperatures on wooden elements and structures. Of these, the most common and cost-effective method of fire protection is the application of special intumescent coatings to the wooden structures of buildings and facilities. These coatings with a small thickness during a fire show high efficiency of fire protection, and when applied to the surface of a structure, modern equipment can be used [5].

However, some technological requirements are imposed on the surface fire-retardant treatment of wooden structures of buildings and facilities. Of these, the following can be noted:

– the moisture content of wooden structures should be no more than 15 %;

– surface treatment should be carried out at a positive temperature and not exceeding 70 % relative humidity;

– before applying the composition, the surface to be treated must be cleaned of dust and dirt.

The results obtained in fire protection practice show that surface coatings do not always provide reliable fire safety of wooden structures of buildings and facilities, i.e., they mainly belong to groups II–III of fire protection efficiency [6].

Therefore, to improve fire safety, especially with load-bearing wooden structures of buildings and facilities, combined methods of fire protection are used, i.e., in addition to surface treatment of wooden structures, they are covered with fire-resistant sheet materials.

In Azerbaijan, the development of means and methods for fire protection of wooden structures has never been carried out. The demand for these materials was covered by deliveries made mainly from Russia, Ukraine, and Belarus. In recent decades, European flame retardants have also begun to arrive. However, for various reasons, the supply of flame retardants is delayed over time or stops altogether, i.e., the stability of the market for these materials is not ensured. On the other hand, the price of these funds often varied within wide limits, there were few of their assortments. It should be noted here that in Azerbaijan there is also no technological base for the preparation of flame retardants and methods for their use. Therefore, there was a need to develop means and methods of fire protection based on available local raw materials and materials, as well as on the appropriate production bases [7]. Taking into account the above provisions, for the development of a flame-retardant composition, nitrogen-phosphorus-containing substances, which are often used in fire retardant practice, can be used as initial components. These substances are partially produced in the republic and there are deliveries from other countries, i.e., no difficulties are expected with the delivery of components.

In recent decades, the construction of individual housing structures and special-purpose facilities, as well as the use of wooden structures and their elements in them, has been expanding in Azerbaijan. Protecting these structures from fire is a top priority for the construction industry. Therefore, the development of means and methods for fire protection of wooden structures in a combined way based on available substances and technical capabilities is relevant.

2. Literature review and problem statement

Now we are analyzing several widespread and industrially used fire-retardant coatings for wooden structures based on nitrogen-phosphorus-containing compounds and epoxy resin.

Paper [8] presents the results of studies of an intumescent fire-retardant coating for wood (GOST 25130-82). The fire-retardant coating was developed on the basis of melamine-carbamide resin (31.9 wt. %), stranded (18.4 %), ammophos-A (27.5 %), and other components. This coating only at a consumption of 750 g/m^2 ensures the fire resistance of wooden structures. This increases the cost of the agent, as well as the thickness of the applied coating, which are accompanied by a decrease in the adhesion and fire hazard properties of the coating.

Paper [9] reports the results of studies of the Terma-S fire-retardant coating, consisting of ammonium polyphosphate (13–33 wt. %), epoxy resin (20–37 %), hollow glass spheres (5–20 %), and other components, it has a relatively high cost. Only the cost of hollow glass spheres is 3–30 $/kg; on the other hand, they are not widely used in the domestic market.

Work [10] presents the results of studies of the foaming refractory composition Firex-500, which is a two-component composition on an inorganic basis, consisting of a paste and an additive. The service life of the prepared mixture is 10–30 minutes, therefore, during application to wooden structures, oone should not allow it to harden. On the other hand, it is necessary to work with the composition of Firex-5000 in a respirator, gloves, and goggles.

Paper [11] reports the results of studies of the fire-retardant intumescent paint Defender W, which is a one-component fire-retardant composition and belongs to imported material. Its consumption is 0.310–0.600 kg/m^2, the cost in the domestic market is 7–8 $/kg. The price of fire-retardant work with this paint is quite high, its primary components are rare substances.

Work [12] presents the results of studies of a water-based intumescent fire-retardant coating (IFR-Na-REC) containing sodium-modified rectorite (Na-REC). The fire-retardant performance of this coating is due to the formation of a ceramic protective layer between the rectorite and the components of the intumescent coating. This coating is characterized by components different in nature and relatively difficult to obtain and the lack of practice in the use of natural rectorite in Azerbaijan.

Paper [13] reports the results of studies of the developed fire-retardant coating for wood based on epoxy-amine composites modified with copper hexafluorosilicates, which has the first group of fire-retardant efficiency. However, the manufacturing process of this fire-retardant coating is relatively complex and requires appropriate preparation conditions and equipment.

Article [14] presents the results of studies of the developed surface coating, which is used on elements of wooden architecture, consisting of two layers. The first layer is made of various phosphorus-containing flame retardants, the second layer is based on epoxy resin and polyurethane composition. The applied method of fire protection of wooden elements can be classified as combined. According to the results of fire tests with an indicator of 5.0–6.4 % weight loss of the samples, the fire-retardant coating belongs to the first group of fire-retardant efficiency. However, the preparation of 2 flame retardant compositions requires additional time and appropriate equipment. On the other hand, the epoxy resin and the polyurethane composition used in the second layer are expensive substances, and the latter has harmful properties.

Work [15] presents the results of studies of a fire-retardant nanocoating based on layered aluminosilicates, nanooxides, nanosilica sol, and nanostructured carbon materials for wood, which is characterized by positive results. Here, the prospects of the research conducted in this direction are substantiated. However, it is necessary to take into account the fact that the use of nanotechnology with appropriate means and production conditions is not always available, and the cost of the work performed is relatively high.

Paper [16] reports the results of studies of a fire-retardant facing method for protecting wooden structures. For this, a 2 mm fire-resistant plywood sheet was used. This sheet was impregnated with a flame retardant, using the technological bath method, and glued on a press machine to the appropriate thickness. The proposed method has a short-term effect of fire protection since, under fire exposure, the facing plywood will lose its protective properties in a short time and the temperature of the structure will rise to a critical moment.

Work [17] presents the results of studies on increasing the fire resistance of fast-growing poplars based on a combined method, using resin for impregnation, and pressing to increase the density of the material. A borate-containing phenol-formaldehyde resin was used as a resin; the compression of the material was carried out in the transverse direction with different intensity. This method of fire protection increases the number of operations involving relatively complex installations and equipment.

The above examples and the state of affairs on the ground on the fire protection of wooden structures confirm the expediency of continuing the study. At the same time, the main goal is to develop a fire-retardant coating and a method for its application based on chemicals that are available and widely used in the domestic market. And also, the establishment of a fire protection mechanism for wooden structures with a developed fire-retardant composition and fire-resistant facing sheet material.

3. The aim and objectives of the study

The aim of this study is to develop a combined method of fire protection to improve the fire resistance of wooden structures of buildings and facilities, based on a fire-retardant surface coating and fire-resistant sheet materials. This will make it possible to ensure the construction of fireproof wooden structures, which will increase the fire resistance of buildings and facilities, especially with enclosing, attic, or mansard types.

To achieve the goal, the following tasks were set:

– to select raw materials available on the domestic market for the development of a fire-retardant coating and determine their optimal content in the composition of the fire-retardant composition;

– to determine the consumption of the developed fire-retardant coating of wooden structures of buildings and facilities that meets the requirements for slow-burning wood materials;

– to choose the means and method of combined fire protection of wooden structures of buildings and facilities, establish the fire hazard properties of the treated structures and determine their fire-retardant efficiency.

4. The study materials and methods

In the work, wooden structures of buildings and facilities were taken as the object of research. To increase their fire resistance, a combined method of fire protection was used. In this technique, in the first stage, the development of a fire-retardant coating was carried out. For this, ammophos-A, ammonium sulfate, intumescent perlite, and epoxy resin were selected as starting materials, the characteristic indicators of which are given below:

Ammophos-A is regulated according to GOST 1891815; structure, light granule; chemical formula $NH_2H_2PO_4$; consists of 9–11 % N and 42–50 % P_2O_5, the N:P_2O_5 ratio varies within 1:4; solubility in 20 °C water, 370 g/l; pH value, 4.0–4.5; melting point >190 deg.

Ammonium sulfate is regulated in accordance with GOST 9097-82; structure, light reddish granule; chemical formula $(NH_4)_2\ SO_4$; consists of 21 % N and 24 % S; solubility at 20 deg. water 75.4 g/100 g; decomposition temperature 218 degrees; melting temperature, 235–280 degrees.

Intumescent perlite is regulated according to GOST 10832-64; white granule structure; mainly consists of 65–70 % silicon dioxide and 10–16 % alumina; water absorption, 400 %; degree of porosity, 8–40 %; thermal insulation coefficient, 0.043–0.052 W/m °C; melting temperature, 1100–1200 deg.

Epoxy resin is regulated according to GOST 57729-2017; structure – light liquid; participation in the composition of epoxy groups 20.0–22.5 %, drying time on the surface is at least 4 hours; viscosity, 12.5–25 s.; ignition temperature, 410 degrees.

To enhance the fire-retardant properties of wooden structures, in addition to the fire-retardant coating applied to them, they were lined with plasterboard sheets, the characteristic indicators of which are presented below.

Plasterboard sheets are regulated according to the standards 6266-97 of the Republic of Azerbaijan; we used sheets with dimensions of 10×1250×2500 mm.

The development of a flame-retardant composition with selected components was carried out in three stages. In the first stage, the content of ammophos-A and ammonium sulfate was changed in the composition in the ratios and limits: 0/30; 5/25; 10/20; 15/15; 20/10; 25/5; 30/0 (wt. %), respectively. The content of other components (expanded perlite 10 %, epoxy resin 50 %) was kept constant. In the experiments, the flame-retardant compositions made according to the indicated ratios of the components were applied to the surfaces of the structures in two layers, and after drying, the samples were subjected to fire tests. At the same time, the following parameters were taken as control parameters: mass loss of samples and time of flame and flameless combustion.

The participation of intumescent perlite in the fire-retardant composition was determined by the same method within the limits: 0, 5, 10, 15, 20 (wt. %), leaving other components constant.

In the third stage, the optimal content of epoxy resin in the fire-retardant composition was established, experimenting it within the limits: 30, 40, 50, 60, 70 (wt%). For this, EP-20 epoxy resin was used.

After establishing the optimal content of all components in the fire-retardant composition, its required amount was determined, applied in two layers on wooden structures. For this flame-retardant composition, the consumption was: 150, 250, 350, 450, 550, 650 g/m^2. With the establishment of the optimal consumption of the flame-retardant composition, its effectiveness was determined in comparison with flame retardant No. 13.

Fire tests of wooden structures with coatings of flame retardants were carried out taking into account the requirements of NPB 251-98 "Fire safety standards. Fire retardant compositions and substances for wood and materials based on it. General requirements. Test methods" in accordance with [18], with interstate standards GOST 16363-98 "Flame retardants for wood. Methods for determining fire-retardant properties" [19] and GOST 30444-97 "Construction materials. Flame propagation test method" [20]. And also, when establishing the effectiveness of fire protection of wooden structures in a combined way, the methodology of the Institute of Wood Chemistry of the Academy of Sciences of Latvia was used [21]. The work also took into account the requirements of the European standard "EN 13501-1:2007 "Fire classification of construction products and building elements", which categorizes building wooden materials and structures into fire resistance classes.

For this, shields were made from solid pine wood with dimensions of 30×250×1100 mm. First, the developed flame-retardant composition was applied to these shields in two layers. After drying the applied coatings, the panels were lined on all sides with plasterboard sheets 10 mm thick. Fire tests were carried out under field conditions. As an ignition source, a flame torch of the "Ceramic tube" method with a flame height of 150 mm was used. The shields were installed vertically, the flame was kept at a distance of 60 mm. During the tests, the following was established: the ignition time of the samples, the length and speed of the flame propagation over the surface of the design samples. The flame propagation velocity was calculated using the formula:

$$Ve=El:Te, \text{ m/min},$$

where El (L) – length of flame propagation over the surface of the structure, m; Te (t) – flame propagation time, min.

5. Results of the study of fire resistance of wooden structures

5. 1. The main parameters for the selection of raw materials of the flame-retardant composition

We carried out the choice of starting materials consisting of: ammophos-A, ammonium sulfate, expanded perlite, and epoxy resin. The first three components as fertilizers are widely used in agriculture and other industries. Epoxy resin is used in the manufacture of various products and parts from polymeric materials, including wood. The choice of these materials was due to their composition and properties, which play an important role in the fire protection of wooden structures. This is due to the fact that ammophos-A contains 9–11 % N and 42–50 % P_2O_5, and its melting point is >190 deg. Ammonium sulfate consists of 21 % N and 24 % S, its melting temperature is 235–280 degrees. Expanded perlite consists of granules, it is characterized by water absorption up to 400 %; melting temperature, 1100–1200 deg. Epoxy resin was chosen as a binder, foaming during fire actions up to an ignition temperature of 410 degrees. The described materials are affordable and widely distributed in the domestic market. The specified parameters of the selected components are prerequisites for conducting a study to obtain a surface fire retardant coating.

5. 1. 1. Investigation of the optimal content of components in a flame-retardant composition

The study of the optimal content of components in the fire-retardant composition was carried out in two stages. In the first stage, the effect of ammonium sulfate and ammophos-A on the fire resistance of wooden structures was studied in the ratios and limits: 30/0; 25/5; 20/10; 15/15; 10/20; 5/25; 0/30, leaving the participation of other components constant. The prepared fire-retardant compositions were applied on the surface of the structure in two layers, after drying of which, the samples were subjected to fire tests. In this case, the weight loss of the samples was determined, as well as, after the removal of the ignition source, the time of their flameless combustion [22].

The research results showed that with a change in the ratio of ammophos-A and ammonium sulfate in the range from 0/30 % to 15/15 % (wt.%), the mass loss of the samples decreases from 17.6 % to 4.2 %, the flameless burning time from 57 s to 28 s, respectively. In the subsequent 20/10, 25/5 and 30/0 % ratios of the components, the fire hazard characteristics of the construction samples gradually increased (Fig. 1).

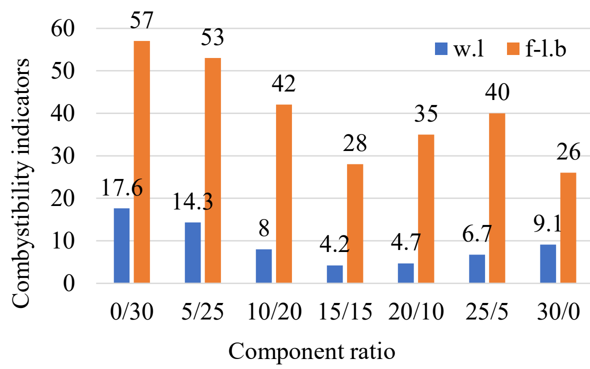

Fig. 1. Dependences of fire hazard indicators of wooden structures on the ratio and amount of ammonium sulfate and ammophos-A in the fire-retardant composition: w.l – weight loss; f-l.b – flameless burning

In the second stage, the content of intumescent perlite in the fire-retardant composition was determined in a similar way. To do this, the content of ammophos-A and ammonium sulfate was taken to be 15 % each, the remaining components were kept constant. The intumescent perlite in the fire-retardant composition was changed within the limits: 0, 5, 10, 15, 20 (wt %). These compositions, prepared according to the indicated recipes, were applied to the surface of the structure in two layers, after drying of which they were subjected to fire tests.

The results of fire tests showed that, by increasing the content of intumescent perlite in the fire-retardant composition from 0 to 10 %, the weight loss of the samples decreased from 18.8 % to 5.1 %. In this case, the viscosity of the flame-retardant composition with the participation of 10 % perlite was 30 – 32 s, pH 4.8 – 5.1.

An increase in the content of intumescent perlite to 15 and 20 % makes the fire-retardant composition thicker, while the viscosity increases from 67–71 s to 118–121 s, respectively.

In the third stage, in order to establish the optimal content of epoxy resin in the fire-retardant composition, it was experimented within: 30, 40, 50, 60, 70 (wt. %). At the same time, the participation of the remaining components was left constant, i.e., ammophos-A 15 %, ammonium sulfate 15 %, intumescent perlite 10 % [9].

The results of fire tests showed that with an increase in the content of epoxy resin in the fire-retardant composition from 30 to 40 %, the weight loss of the samples decreased from 12.6 to 5.2 %. That is, with an increase in the amount of resin, the adhesion strength between the wood and the fire-retardant coating increases. On the other hand, there is an increase in the thickness of the foaming charred layer on the surface of the structure, which insulates the surfaces from fire and temperature rise. The need to increase the content of epoxy resin up to 50 (wt. % was associated with the instability of the obtained fire hazard characteristics of the structure).

However, the expediency of increasing the content of epoxy resin in the composition was determined by the fact that the weight loss indices of the samples were unstable and varied relatively within large limits (5.2–7.4 %). At the same time, the flameless burning time (24–38 s) slightly exceeded the requirements for slow-burning wood materials.

The results obtained during fire tests showed that the weight loss of the samples varied within 4.3–5.2 %, and flameless combustion 22–29 s. In this case, a foamed charred layer up to 4–6 mm thick is formed on the sample surface. At the same time, it was found that the adhesion of this layer to wood is quite high, and cracking and partial detachment of the fire-retardant coating from the wood surface do not occur.

With an increase in the resin content in the flame-retardant composition to 60 and 70 wt.%, the weight loss of the samples tends to increase in the range of 6.6–8.3 %. This was due to the destruction of the charred layer formed on the surface with the participation of epoxy resin, the ignition temperature of which is 410 °C. On the other hand, an increase in the content of epoxy resin will increase the cost of fire retardant composition (the cost of epoxy resin is 13504 man./t), which will lead to a narrowing of its application area [23].

5. 2. Investigation of the effect of AS-143 flame retardant consumption on the fire hazardous properties of wooden structures

The consumption of the developed flame-retardant composition was determined. To do this, the following were applied to the surface of the construction samples: 150, 250, 350, 450, 550, 650 g/m² of fire-retardant compositions. During fire tests, the weight loss of the samples, the time of their flame and flameless combustion were determined. The test results are displayed on the plot (Fig. 2).

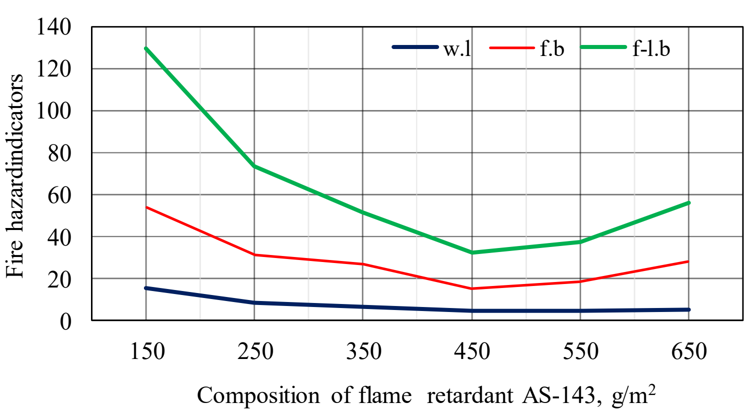

Fig. 2. Dependences of fire hazard indicators of wooden structures on the consumption of fire-retardant composition: w.l — weight loss, %; f.b — flaming burning, sec; f-l.b — flameless burning, sec

As can be seen from Fig. 2, at a consumption of the flame-retardant composition of 150 g/m² and 250 g/m², the weight loss of the samples is reduced from 15.6 % to 8.5 %, the time of their flame burning from 38 s to 23 s, and flameless burning from 76 s to 42 s. With an increase in the consumption of the flame-retardant composition to 350 g/m² and 450 g/m², the weight loss of the samples decreased to 6.8 % and 4.5 %, the flame burning time – to 20 s and 11 s, and the flameless time was down to 25 s and 17 s respectively. With a further increase in the consumption of the flame-retardant composition to 550 g/m² and 650 g/m², there is no sharp decrease in the fire hazard characteristics of the structure [24].

The results obtained make it expedient to keep the consumption of the flame retardant, depending on the operating conditions of wooden structures, at the limit of 350–500 g/m². The consumption of this composition is recommended to be taken, in unheated rooms 350–450 g/m², in heated rooms 400–500 g/m².

After establishing the optimal content of components and the consumption of the developed fire-retardant composition (in the following descriptions, flame retardant AS-143 will be designated), its effectiveness was determined in comparison with fire retardant No. 13. To do this, flame retardant AS-143 and flame-retardant No. 13 were applied to the surface of samples of wooden structures at a consumption of 200, 300, 400, 500, 600, 700 g/m². A graphic representation of the results of fire tests of samples is shown in Fig. 3.

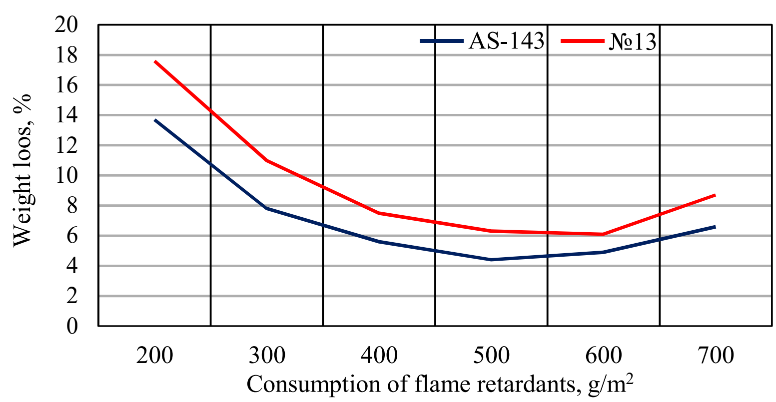

Fig. 3. Dependences of fire hazard indicators of wooden structures on the consumption of flame retardants: 1 – AS-143; 2 – No. 13

Fig. 3 shows that at the consumption of both flame retardants 200 g/m² and 300 g/m², the weight loss of the design samples was: those containing AS-143 flame retardant 14.1 % and 7.9 %; flame retardant No. 13 – 17.6 % and 11.0 %, respectively. Increasing the consumption of these fire retardants to 400 and 500 g/m² improves the fire hazard characteristics of wooden structures. These indicators for structural samples treated with flame retardant AS-143 were: weight loss 5.6 % and 4.4 %, flame burning time 18 s and 13 s, flameless 25 s and 22 s, respectively. For design samples treated with flame retardant No. 13, these indicators were, respectively, 7.5 % and 6.3 %; 30 s and 24 s; 52 s and 43 s. As can be seen, with an increase in the consumption of fire retardants up to 500 g/m², the fire resistance effect with fire retardant AS-143, in comparison with flame retardant No. 13, improves by 43.2 % in terms of weight loss.

An increase in the consumption of these flame retardants to 600 and 700 g/m^2 in both variants is accompanied by a deterioration in the fire hazard characteristics of wooden structure samples. The results of fire tests showed that the weight loss of the structure samples treated with AS-143 flame retardant was 4.9 % and 6.6 %, flame burning time was 19 s and 31 s, flameless burning was 26 s and 39 s, respectively. These figures with flame retardant No. 13 were, respectively, 6.1 % and 8.7 %; 22 s and 37 s; 38 s and 55 s.

As can be seen, the results obtained show that with an increase in the consumption of fire retardants from 600 g/m^2 to 700 g/m^2, the fire hazard characteristics of the design samples in both options tend to deteriorate.

5. 3. The choice of means and method of combined fire protection of wooden structures

In the work, for the combined fire protection of wooden structures, chemical and structural methods were used. In the chemical method of fire protection, the developed composition AS-143 based on ammophos-A, ammonium sulfate, expanded perlite, and epoxy resin was used for the surface fire retardant coating of wooden structures. To do this, the fire-retardant composition was applied to the structures in two layers.

With the structural method of fire protection, after drying the applied layers of the composition, samples of wooden structures were lined with fire-resistant sheet materials. As these materials, gypsum boards were used, the thermal performance of which is presented above. In the course of fire tests, the ignition time of the samples was set for 10 minutes, the length and speed of flame propagation over the surface of the structure samples for 30 minutes.

The results of fire tests showed that the samples did not ignite for 10 minutes under the influence of an ignition source. With continued exposure to the flame for 30 min, partial and short-term (5–9 s) ignition and decomposition of gypsum plasterboard linings were found on the surface of the samples. At the same time, the length of flame propagation over the surface of the structure was determined for 30 minutes. This parameter was determined from the burnt surface of the structural samples, which changed within 456–678 mm. The calculation of the speed of flame propagation over the surface of the structural specimens was carried out on the basis of the obtained data on the length of flame propagation on the specimens, which were in the range of 0.015–0.023 m/min.

6. Discussion of results of the study of fire resistance of wooden structures

In the work, the choice of components of the fire-retardant coating was carried out with their availability and wide distribution in the domestic market, transportability, safety, and ease of use. On the other hand, the ammophos-A and ammonium sulfate involved in the composition of the fire-retardant coating mainly consist of phosphorus- and nitrogen-containing compounds, which have high flame-retardant properties. The interaction of these components is synergistic in nature, which manifests itself in a gradual slowdown in the efficiency of the combustion process. Here the nitrogen compounds aid the phosphorulation process by inhibiting the oxidation of carbon creating a purge effect in the gas phase. In the process of combustion under the influence of high temperatures, phosphoric acid is released and exhibits its flame-retardant properties [25].

Another selected component, expanded perlite, has a high heat resistance and swelling on the surface of the wood creates a shielding heat-insulating layer of a certain thickness.

In studies, the application of the method for determining the optimal content of components in a fire-retardant composition and the results obtained are explained by the following features. When fire-retardant treatment of wooden structures, the effect of fire protection depends on the choice of the optimal ratio of phosphorus and nitrogen-containing compounds in the fire-retardant composition; phosphorus content in the flame-retardant composition.

In most flame-retardant compositions, the optimal nitrogen-phosphorus ratio (N/P) for a number of phosphorus-containing systems, depending on the degree of condensation and the type of nitrogen-containing compounds, is set within the range of up to 5–8. This ratio can be considered acceptable only in the case when the structures are pre-treated with fire retardants. In fire-retardant practice, in order to obtain slow-burning wood materials, the presence of phosphorus in a fire-retardant composition should be 2.5–3.0 %, as the main condition for obtaining [5].

In the studies carried out, the optimal ratio of nitrogen-phosphorus (N/P) in the fire-retardant composition was set within 1 – 1.5:1 – 1.5, and the optimal phosphorus content was about 2 %. From Fig. 1 it can be seen that wooden structures treated with a fire-retardant composition with the appropriate content of nitrogen-phosphorus compounds provide with a weight loss during fire tests of 4.5–5.2 %, the first group of fire-retardant efficiency.

The studies revealed that with an increase in the content of ammophos-A in the composition up to 20, 25, 30 wt. %, bubbles form on the surface of the coating after applying the first layer, and after the second layer, the number of bubbles increased. At the same time, a decrease in the adhesion strength of the fire-retardant coating to the wood surface was observed, which was accompanied by an increase in the mass loss of the samples during fire tests from 4.7 % to 9.1 %, reflected in Fig. 1. It has also been established that even with a slight impact on such coatings, it leads to the formation of cracks on them and its delamination from the surface of the structure [26].

The studies revealed that with an increase in the participation of intumescent perlite in the composition to 15 and 20 %, it is accompanied by a decrease in the viscosity of the fire-retardant composition from 67–71 s to 118–121 s. This makes it impossible to uniformly apply the composition to the surface of the structure, therefore, the adhesive strength between them becomes weak, which affects their fire hazard characteristics [27].

From Fig. 2 it can be seen that with an increase in the consumption of fire retardant AS-143 to 550 g/m^2 and 650 g/m^2, it is accompanied by a gradual increase in the fire hazard characteristics of wooden structure samples during fire tests. This is explained by an increase in the thickness of fire-retardant coatings formed on the surfaces of structures and a decrease in the adhesion strength of this coating to wood complexes. As a result, fire-retardant coatings under the influence of fire and pressure of moisture separated from the inner layers of wood undergo cracking. At the next stage, with the expansion of cracks and the direct impact of the flame on the wood substance, its destruction is accelerated, which causes an increase in weight loss and a deterioration in other fire resistance indicators [28].

The work also determined the effectiveness of the developed flame-retardant composition AS-143 in comparison with fire retardant No. 13. From Fig. 3 it can be seen that with an increase in the consumption of fire retardants to 500 g/m^2, the effect of fire resistance of wooden structures, with fire retardant AS-143, in comparison with fire retardant No. 13 in terms of weight loss improves by 43.2 %. This is due to the correct choice of the ratio of nitrogen and phosphorus-containing compounds in the fire-retardant composition AS-143, as well as the participation of about 2 wt.% phosphorus in this composition.

It was found in the studies that, during fire tests, wooden structures treated in a combined way in terms of weight loss of samples does not exceed 6 %, in terms of the speed of flame propagation over the surface, they vary in the range of 0.015–0.023 m/min. The research results confirm that the wooden structures of buildings and facilities treated with combined fire protection methods meet the requirements for slow-burning materials.

Wooden structures treated with a surface coating and lined with gypsum-cardboard sheets with the obtained fire hazard indicators belong to group I of fire-retardant efficiency. These structures can be safely implemented in the construction of buildings and facilities, especially with enclosing, attic, or attic types.

In the conducted studies, the increase in the content of ammophos-A over more than 15 wt.%, expanded perlite – more than 10 wt. %, leads to a decrease in the fire-resistant properties of the fire-retardant coating and its adhesion strength to the wood surface. The first layer of fire-retardant coating applied to the surfaces of structures must be dried for 6–8 hours at room temperature or at 40 °C in an oven for 2 hours. Batch-prepared flame-retardant compositions must be applied within 2–3 hours with partial mixing.

At the subsequent stages of research development, it is necessary to study the process of thermal decomposition of fireproof wooden structures and the formed chemical bonds between the coating and wood when exposed to high temperature.

On the other hand, in the composition of the fire-retardant coating, the content and cost of epoxy resin is slightly high, amounting to 30 wt.% and about 7943.5 $/t. In order to ensure the wide availability of the developed fire-retardant coating with the participation of epoxy resin, it is planned to replace it with components with a lower cost in the subsequent stages of the study.

7. Conclusions

1. A fire-retardant surface coating has been developed with an optimal ratio of components 15:15:10:50 wt.%, respectively, ammophos-A, ammonium sulfate, expanded perlite, and epoxy resin. The results of fire tests of wooden structures treated with the same coating showed that the weight loss of the structure samples was 4.5–5.2 %, flame combustion (after the ignition source was removed) 23–29 s, flameless 34–42 s.

2. It has been established that the consumption of flame retardant for wooden structures is: in unheated premises 350–450 g/m^2, in heated premises 400–500 g/m^2. The results of fire tests showed that the treated structures with the indicated costs of the fire-retardant coating in terms of the degree of fire resistance are classified as slow-burning materials.

3. It has been established that wooden structures, fire-protected in a combined way with the use of a surface coating and facing plasterboard sheets, provide reliable fire protection of these structures. The results of fire tests showed that the samples of these structures did not ignite within 10 minutes after the fire was applied, and after 30 minutes the plasterboard layer, decomposing, split off. In this case, the weight loss of the specimens does not exceed 6 %, and the flame propagation velocity over the surface of the structure varied in the range 0.015–0.023 m/min. The obtained parameters for the fire-retardant efficiency of wooden structures correspond to group I. These structures can be safely used in the construction of buildings and facilities.

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 and the results reported in this paper.

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Data availability

All data are available in the main text of the manuscript.

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