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STUDY OF THE INFLUENCE OF SODIUM HEXAMETAPHOSPHATE ON THE PROPERTIES OF SILICA-CONTAINING FIREPROOFING COATING FOR BUILDING MATERIALS

The composition of a silicophosphate composition intended for fire protection of building materials was developed. Solutions of liquid glass, acetic acid and sodium hexametaphosphate were used as starting components. The influence of the content of the phosphorus-containing additive on the rheological properties of silicic acid sols was studied. By spectrophotometry, it was established that the latent coagulation time in the entire range of the studied content of sodium hexametaphosphate is ~20 minutes. The highest values of optical density were recorded for a sol with an additive content of 0.3 %. The probability of the influence of electrostatic and steric effects, which depend on the concentration of the phosphorus-containing additive, on the stability of the sol was considered. It is assumed that the minimum value of sol survivability at 0.3 % of the additive is associated with a decrease in the ζ-potential and compression of the double electric layer. The results of infrared spectroscopy confirmed the hypothesis of two different mechanisms of polycondensation in different intervals of hexametaphosphate content. At a content below 0.3 %, a linear mechanism of polycondensation was noted, above 0.3 % – a reticular one. Fire tests were carried out on samples of wood and extruded polystyrene foam coated with compositions of the studied composition. The best fire-retardant properties were recorded for systems with a sodium hexametaphosphate content of 0.1–0.3 %. Processing of wood samples allowed transferring the material to the “hard-to-flame” group, the mass losses of the samples were less than 10 %. Samples of extruded polystyrene foam did not support combustion at an additive content of 0.1 % or did not burn at all at a content of 0.3%, mass losses were less than 3 %. The effect of the number of coating layers on the effectiveness of its fire-retardant action was assessed: for wood in the range of hexametaphosphate concentrations of 0.1–0.3 %, three-layer coatings were the most heat-resistant, for extruded polystyrene foam at a content of 0.3 % – one- and two-layer.

Keywords: fire-retardant silica-containing coatings, sodium hexametaphosphate, building materials, heat resistance, fire resistance, wood, polystyrene foam

1. Introduction

Today, the issue of energy efficiency is becoming one of the most global challenges for society in the context of reducing energy consumption, the rational use of which is also relevant and necessary given the depletion of traditional energy sources – oil, gas and coal.

According to the Law of Ukraine "On Energy Efficiency of Buildings", one of the main principles of state policy in this area is to ensure thermal modernization of buildings. It is also known that one of the mandatory documents in the technical passport of a residential building is an energy certificate, which reflects the energy efficiency class with the corresponding indicators (order of the Ministry of Regional Development, Construction and Housing and Communal Services of Ukraine dated July 11, 2018 № 172).

In the private sector, wood is quite often used as the main building material, which has natural thermal insulation properties. However, to achieve the required level of energy efficiency, external insulation of buildings is necessary, which is one of the simplest and most effective ways of thermal modernization. According to the requirements of DBN V.2.6-33:2018 “External wall structures with facade thermal insulation. Design requirements”, only non-combustible materials or materials with low (group G1) or moderate (group G2) flammability can be used. However, building owners quite often neglect the requirements of safety standards, choosing more affordable alternatives to insulation materials. This, in particular, is extruded polystyrene foam, which, despite its numerous advantages, is flammable (group G3–G4).

The risk of fire due to the ignition of the above-mentioned materials can be reduced by using fire protection systems, among which silica coatings attract special attention, which form a reliable thermal insulation barrier under the influence of high temperatures. It is known that to increase the effectiveness of fire protection, it is advisable to use multicomponent systems. The most popular and widely used flame retardants are phosphorus-containing compounds. Such substances are able to inhibit combustion reactions, both in the solid phase, due to the activation of the polymer carbonization process, and in the gas phase – by deactivating radicals in the flame. Phosphorus compounds, integrated into siloxane chains, contribute to the formation of silicophosphate systems, which are characterized by thermal stability and low chemical activity. The starting components for the formation of such compositions can be synergists and will have a total effect of improving fire resistance. However, cases of antagonism may be quite possible, when the compounds reduce or even completely eliminate the positive effect of each other.

Therefore, the issue of finding components of the silicophosphate composition that would harmoniously complement each other’s advantages is key to creating a reliable and effective fire-retardant coating for building materials.

2. Analysis of literary data and problem statement

It is well known that inorganic phosphorus-based compounds have better properties than organic ones, in particular, due to higher thermal stability, lower toxicity, lower smoke generation and volatility. Therefore, most scientific works are devoted to the study of the flame-retardant properties of phosphorus-containing substances on an inorganic basis.

The authors of the work [1] investigated the inhibitory effect of three P-flame retardants on coal self-ignition. The properties of sodium orthophosphate, sodium hexametaphosphate and ammonium polyphosphate were studied by mixing raw coal and an inhibitor solution (10 wt.%) in a significant ratio of 4:1. It was found that the best suppressive effect of low-temperature oxidation of coal is provided by the addition of ammonium polyphosphate, which was confirmed in particular by the data of infrared spectrograms of the evolved gases: the maximum temperatures of gaseous products (CO_2, CH_4, CO and H_2O) were significantly reduced due to the deactivation of free radicals. The results of the work [1] have significant practical value, but it is worth noting that the inhibitor content was fixed, the effect of other concentrations was not investigated, which, perhaps, would have allowed optimizing the use of these flame retardants in terms of efficiency and cost-effectiveness.

The flame-retardant content is of great importance for achieving a balance between ensuring effective fire protection of the material and preserving its operational characteristics. The problem of overloading polymers with such compounds was considered in [2]. Styrene composites containing 15 wt.% aluminum hypophosphite or 15 wt.% expandable graphite did not withstand the UL-94 vertical burning test, while polymers with 10 wt.% phosphorus-containing flame retardant and 5 wt.% graphite passed this test. With the synergistic action of flame retardants, a more significant degree of carbonization was also observed. The results of the study are certainly valuable for the theoretical understanding of the above-mentioned issues, but a disadvantage of the proposed method for increasing the fire resistance of polystyrene may be the high cost of expandable graphite, which limits the use of the above composition in mass production conditions.

When choosing a phosphorus-containing compound, it is important to ensure a high mass fraction of phosphorus. Given this requirement for a component of a fire-retardant composition, it is advisable to use pure phosphorus to maximize the amount of the active element. For example, in work [3], red phosphorus and expandable graphite were used as flame retardants. This combination allowed to reduce the peak heat release rate during the combustion of polystyrene to 180.67 kW/m 2 , which was 72.9 % lower than that of the pure sample. The authors of work [4] proposed a fire-retardant composition for impact-resistant polystyrene based on microencapsulated red phosphorus and magnesium hydroxide. The synergistic effect of the two components contributed to a significant reduction in the limiting oxygen index during the combustion of the polymer. The introduction of phosphorus accelerated the endothermic degradation of the hydroxide and contributed to the intensification of the charring process. Despite the importance of the theoretical results of the works [3, 4], a significant limitation when using the proposed compositions may be the low solubility of phosphorus in aqueous media, which accordingly complicates the uniform distribution of the flame retardant and may lead to a decrease in the effectiveness of fire protection.

Many researchers use a strategy to increase the fire resistance of polystyrene, which is based on the inhibitory effect of components in both the condensed and gas phases [5]. This effect can often be achieved due to the synergy of the following elements: P–N, P–Si or P–N–Si. For example, in the study [6], such a flame retardant was obtained by the interaction between N –β-(aminoethyl)-γ-aminopropyltrimethoxysilane and phosphoric acid. The technological feature of the process of creating a fire-retardant system, which consisted in applying the resulting composition to the surface of polystyrene, made it possible to preserve its basic physical properties (density and compressive strength). However, the results of the work [6] showed that the proposed combination of compounds did not allow to significantly reduce the load on the polymer: the lowest content of flame retardant required to achieve a V-0 rating in the UL-94 test was quite high – about 40 wt.%. In addition, the silicon-containing component was organic, which calls into question its environmental friendliness.

Fire retardant compositions based on silicic acid sols are characterized by relatively high safety and thermal stability. Taking into account the effectiveness of multicomponent systems, previously conducted studies were devoted to the complex effect of silica together with orthophosphoric acid [7] and phosphate buffer solutions [8] on the effectiveness of fire-retardant coatings. Based on the considered compositions [7, 8], fire-retardant coatings were created that significantly reduced the combustibility and flammability of wood and extruded polystyrene foam. However, taking into account modern trends in the improvement and rationalization of multicomponent systems, there is a need to find an alternative that could provide additional advantages. In this aspect, the use of sodium hexametaphosphate may be promising, one of the features of which is the high phosphorus content (in terms of P_2O_5 over 63 %) among phosphates produced industrially. This unique characteristic of it can provide significant savings in large-scale production of fire-retardant compositions, reducing material costs. The compound is non-toxic and biodegradable.

In addition, there are works in which this component was used as a dispersant, which contributed to the stabilization of colloidal systems and prevented premature aggregation of particles [9–11]. Therefore, it can be assumed that the use of hexametaphosphate in silica-containing compositions will provide the opportunity to create coatings with high fire-retardant efficiency and appropriate mechanical and physico-chemical properties.

3. Purpose and objectives of the study

The purpose of the work is to study the influence of sodium hexametaphosphate on the formation of the structure and fire-retardant properties of silica-based coatings.

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

– to study the rheological properties of silicic acid sols modified with sodium hexametaphosphate and the gelation processes in them;

– to perform fire tests of wood and extruded polystyrene foam samples to assess the effectiveness of the fire-retardant silicophosphate coating.

4. Materials and research methods

The object of research is the technology of increasing the fire resistance of finishing building materials made of wood and extruded polystyrene foam.

The subject of research is the physicochemical behavior of fire-retardant coatings during fire exposure.

The main hypothesis of the research is the synergistic effect of silicon and phosphorus compounds, which ensures an increase in the efficiency of the fire-retardant coating.

The solutions of liquid glass and acetic acid were mixed using a magnetic stirrer. A solution of sodium hexametaphosphate (SHMP) was added to the obtained silicic acid sols, the content of which was varied within the range of 0.01–1 wt. %.

The rheological properties of the sols were investigated by determining the change in optical density over time using a KFK-2 photo colorimeter using a cuvette with l=5 cm at a wavelength of 490 nm. Distilled water was taken as a reference solution.

Heat treatment of silica gels was carried out at 800 ºC in an oxidizing environment (air), maintaining at a maximum temperature for 2 h (temperature rise rate 4–5 ºC/min).

For raw and heat-treated gels, infrared absorption spectra were recorded on an FTIR-8400S spectrometer equipped with a QATR 10 (Shimadzu) attachment in the range of 400–4000 cm–1. IRsolution and ACD/Lab's software were used to analyze the spectra.

The resulting compositions were applied to the surface of experimental samples by the bath method. Wood samples measuring 9x6x3 cm were used, previously dried to constant mass in a drying oven at 100 °C, as well as samples of extruded polystyrene foam of the XPS brand measuring 5x5x3 cm. 2–3 layers of coating were applied after drying the previous layer at 80°C in a drying oven. Additionally, a 20 % aqueous solution of ammonium dihydrogen phosphate was sprayed onto the surface of the dried samples, after which they were dried.

The fire protection efficiency group of coatings on the surface of wood was determined according to DSTU 4479:2005 [12], the flammability group according to DSTU 8829:2019 [13].

Samples of extruded polystyrene foam were weighed before and after exposure to fire for 10 s, and the mass loss was expressed in percent.

5. Study of the influence of sodium hexametaphosphate on the rheological properties of experimental sols and gelation processes

The curves of changes in the optical density of sols over time depending on the HMP content are presented in Fig. 1.

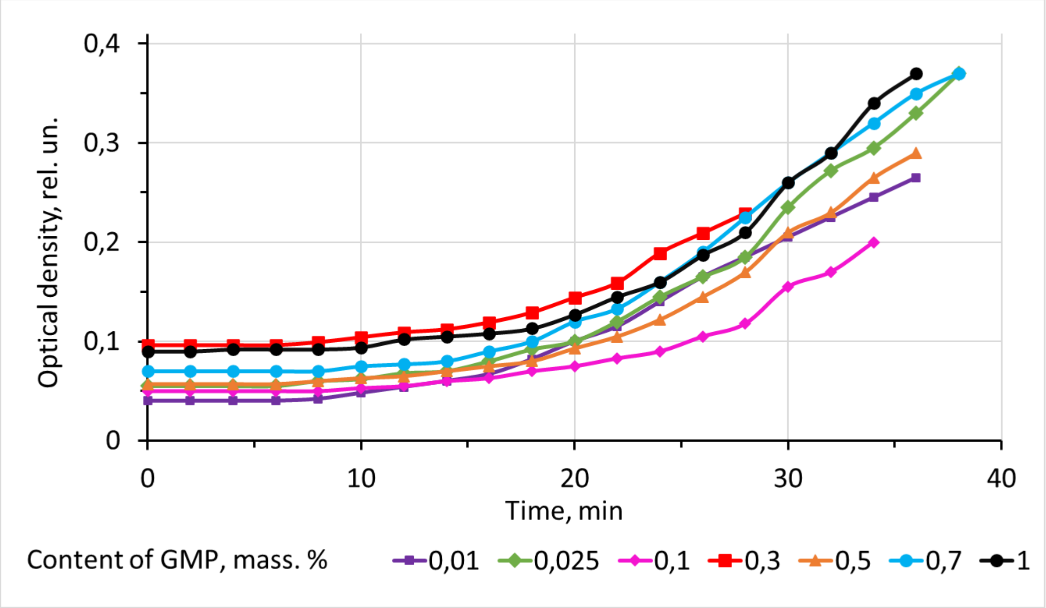

Fig. 1. Dependence of the change in optical density of experimental silicic acid sols with SHMP additives over time

On the graph, the dependences are identical in nature. Almost the same increase in the angle of inclination of the tangents to the curves shows that the process of growth of colloidal particles and their aggregation into associates begins for all compositions, regardless of the additive content, after approximately 20 min.

The dependence for the SHMP concentration of 0.3 % demonstrates noticeably higher values of optical density compared to other concentrations at all stages of measurement. Probably, under the conditions of such an additive content, particle aggregation occurs most intensively. It is also worth noting that the initial values of optical density are directly proportional to the SHMP content in the compositions.

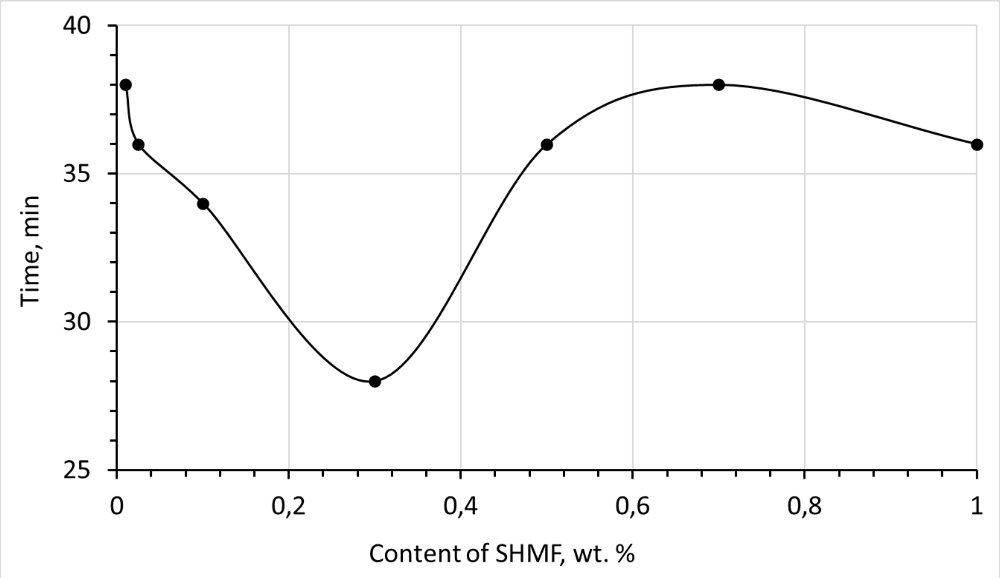

Fig. 2 Shows the dependence of the survival time of sols on the SHMP content

For a concentration of 0.3 %, a minimum is observed on the graph. This dependence, apparently, correlates well with the maximum values of optical density at this SHMP content, compared to compositions with a different quantitative composition.

It can be assumed that the presence of a minimum on the graph is associated with a change in the electrokinetic potential when a non-indifferent electrolyte is introduced into the system.

For dispersed systems, an important role is played by an electric double layer (EDL), which, as a rule, is formed at the interface of two phases from spatially separated electric charges of opposite sign. The potential jump that occurs at the interface of the adsorption (Stern layer) and diffusion parts of the EDL during electrokinetic phenomena is the ζ-potential.

Silicic acid sol is capable of forming a significant amount of OH^-, $HSiO_3^-$ and SiO_3^{2-} ions as a result of hydrolysis and ionization processes. These anions are quite densely adsorbed in the Stern layer on the surface of silica particles (Fig. 3, a).

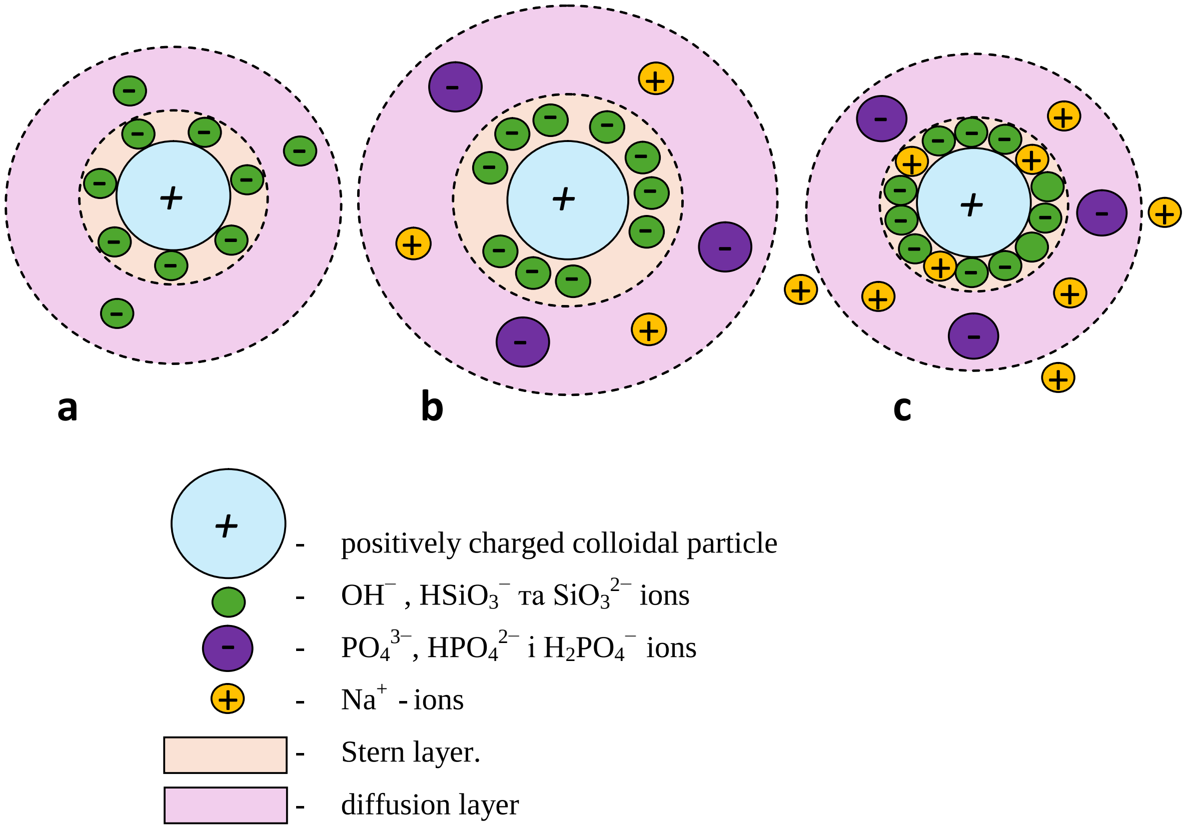

Fig. 3. Scheme of the dependence of the electric double layer and electrokinetic potential for silicic acid sols: a – without SHMP, b – with a low SHMP content; c – with a high SHMP content

Sodium hexametaphosphate in solution can also hydrolyze to form PO_4^{3-}, HPO_4^{2-} and H_2PO_4– anions. Accordingly, a larger number of anions is adsorbed in the Stern layer, which leads to the expansion of the EDL between neighboring SiO_2 particles. The absolute value of the electrokinetic potential increases (Fig. 3, b).

With a further increase in the concentration of SHMP, the number of anions increases, but the number of ions of the opposite charge (counterions) Na+ also increases, so they diffuse from the diffusion layer into the adsorption layer under the action of electrostatic repulsion forces. In this case, the EDL is compressed and the absolute value of the ζ-potential decreases (Fig. 3, c).

All IR absorption spectra of raw SiO_2 gels modified with sodium hexametaphosphate had the same set of characteristic bands. Fig. 4 shows the IR absorption spectrum for silica gel with a SHMP content of 0.7 %.

In all IR spectra of silica gels with different SHMP contents, a broad band is visible in the range of 2800-3600 cm^{-1}, which characterizes the stretching vibrations of O–H bonds. This may indicate the presence of silanol groups or adsorbed water. It is worth noting that with a GMP content of 0.025 to 0.5 %, separate peaks at 3160, 3270 and 3400 cm^{-1} are observed in such a broad band.

For gels with an additive concentration of 0.7 and 1 %, the band in the range of 2800–3600 cm^{-1} is more intense and smoothed.

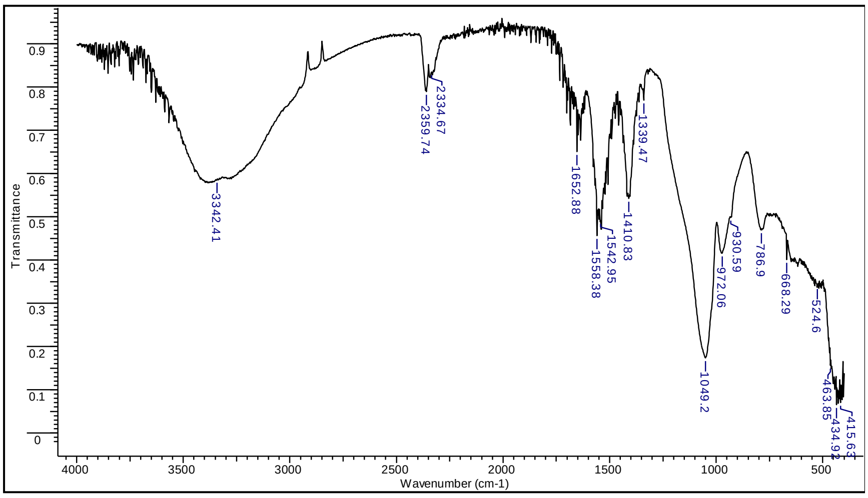

Fig. 4. IR spectra of raw SiO_2 gels with a SHMP content of 0.7 wt. %

As for other studied silica systems described earlier [14], the IR spectra of SiO_2 gels modified with SHMP show rather intense absorption bands at 1410, 1540 and 1635 cm^{-1}, which characterize the deformation vibrations of hydroxyl groups [15].

The spectra of gels with a SHMP content of 0.025–0.5 % are characterized by the presence of a small peak at 1020 cm^{-1}, which also characterizes the valence asymmetric vibrations of siloxane bonds, as well as the band at 1050 cm^{-1} [16].

In the range of 400–470 cm^{-1}, deformation vibrations of Si-O-Si bonds are usually recorded. For gels with a 0.7–1% SHMP content, the intensity of the bands in this range is relatively higher.

The vibrations of the P–O bonds are recorded in the range of 650–800 cm–1. In the range of 500–530 cm^{-1}, vibrations of the bonds in the PO_4^{3-} groups appear. In the spectra of all compositions, the most pronounced bands are at 517 cm^{-1} and 670 cm^{-1}.

To analyze the characteristic absorption bands corresponding to the vibrations of silanol (970 cm^{-1}) and siloxane bonds (790 and 1050 cm^{-1}), their relative intensity was estimated (Fig. 5).

It is not difficult to notice that at a SHMF content of 0.3 % in the composition all bands have the lowest intensity. At additive concentrations of 0.7 and 1 %, the intensity of the absorption bands at 1050 cm^{-1}, which characterizes the vibrations of Si-O-Si bonds, is significantly higher compared to compositions with other quantitative contents. To establish the nature of polycondensation in silicic acid sols, the ratio of the intensity of the band at 1050 cm^{-1} to its half-width – the I/d index (Fig. 6) was estimated.

It is known that the ratio of the intensity to the half-width of the characteristic band of the Si-O bond vibrations at 1050 cm^{-1} indirectly indicates the nature of the polycondensation of polysilicic acid: the smaller this value, the more likely linear polycondensation, however, an increase in C/d indicates the appearance of network blocks in the siloxane chain [14]. In the range of SHMP concentrations of 0.025–0.3 %, the I/d ratio decreases, reaching a minimum at 0.3 %. It was at this additive content that the maximum values of optical density and the minimum survivability of the sol were observed. At high SHMP concentrations (more than 0.3 %), the I/d index increases, therefore, conditions are created for the course of network polycondensation, which contributes to the formation of rigid structures.

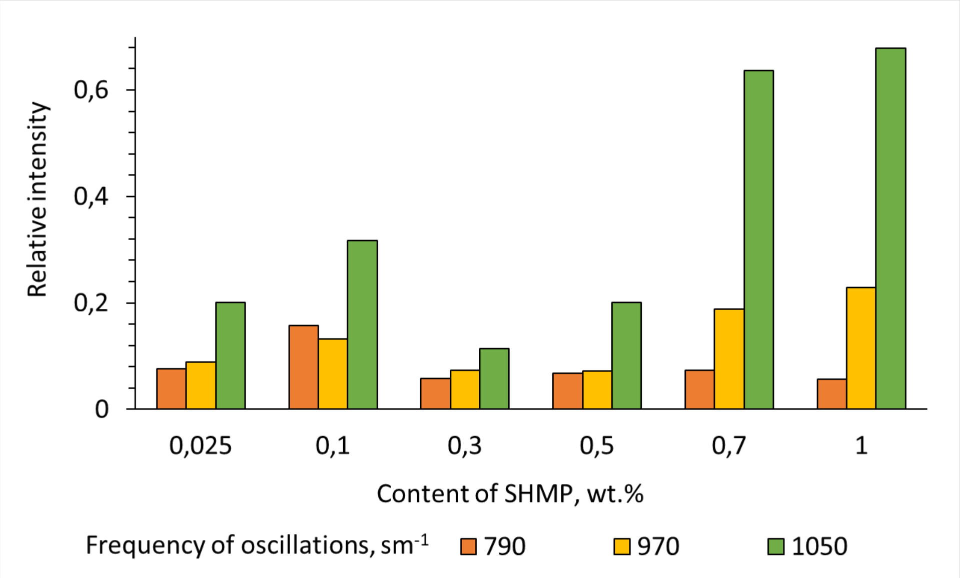

Fig. 5. Change in relative intensity of characteristic bands of raw SiO_2 gels with sodium hexametaphosphate additives

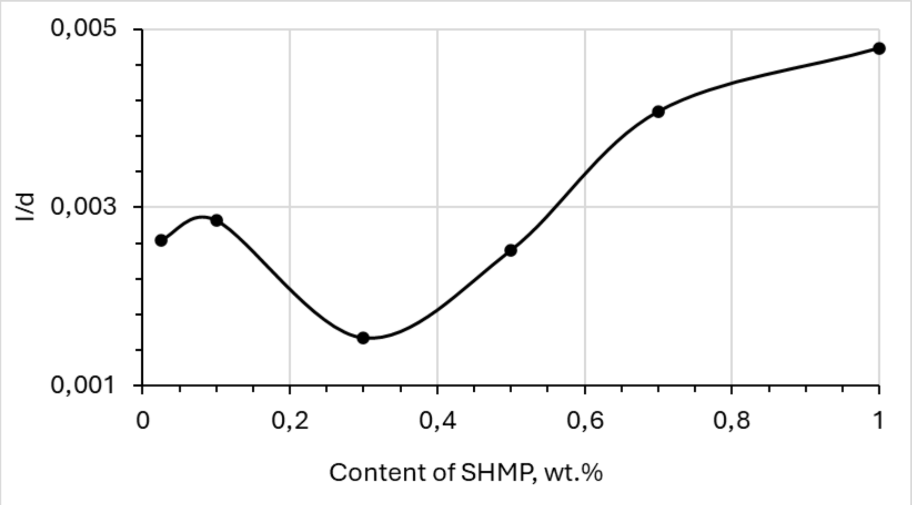

Fig. 6. Influence of sodium hexametaphosphate content on the nature of polycondensation in SiO_2 gels

For the absorption spectra of heat-treated SiO_2 gels modified with sodium hexametaphosphate, the disappearance of the absorption band in the range of 2800–3600 cm^{-1} is observed in the entire range of SHMP concentrations as a result of water removal. The formation of a broad band in the range of 800–1200 cm^{-1} is noted, but for gels with a SHMP addition of 0.025–0.3 %, this band shows a noticeable separation of individual peaks at 920 and 1030 cm^{-1}, while for samples with an additive concentration of 0.5–1 %, the band is more smoothed and uniform.

6. Results of determining the fire-retardant efficiency of silicophosphate coating on wooden samples

Tabl. 1 shows the results of establishing the fire protection efficiency group of the coating and the flammability class for wood samples.

Tabl. 1. Results of studies on determining the fire protection efficiency group and flammability class for wood samples

№	SHMP content, %	Number of coating layers	Sample mass loss (120 s), %	Coating fire protection efficiency group	ΔT_{max}, °C	Time to reach maximum temperature, c	Sample mass loss, %	Combustibility
1	0.1	1	7.51	I	90	390	34.13	flammable, highly flammable
2		2	9.2	II	84	500	41.39	
3		3	8.95	I	91	400	33.72	
4	0.3	1	7.9	I	104	590	57.43	
5		2	9.73	II	75	550	40.63	
6		3	9.89	II	80	560	39.34	
7	0.5	1	11.97	II	120	170	20.84	flammable, medium flammability
8		2	10.42	II	110	200	34.41	
9		3	8.46	I	115	200	29.82	

Thanks to coatings with a SHMF content of 0.1–0.3 %, wood samples were transferred from the group of highly flammable to the group of low-flammability. The mass losses of the samples during 2 min of fire tests ranged from 7.5 to 9.9 %, which corresponds to groups I–II of the fire-protective efficiency of the coatings. It should be noted that the time to reach the maximum temperature for samples coated with compositions with a GMF content of 0.3 % was higher (550–590 s) than for similar ones with 0.1 % GMF (390–500 s). Samples with coatings based on compositions with 0.5 % GMF had average flammability and had a relatively shortest time to reach the maximum temperature (170–200 s).

For experimental samples coated with compositions with a sodium hexametaphosphate content of 0.1–0.3 %, lower mass losses of the samples were observed. In this interval, single- and double-layer coatings gave almost the same fire-retardant efficiency indicators. At a content of 0.5 %, the mass losses of the samples were inversely proportional to the number of coating layers.

Fig. 7 shows the dependence of the mass loss of the samples during 2 min of fire tests on the number of coating layers. The lowest mass losses are provided by a single-layer coating in the range of SHMP content of 0.1–0.3 %. Relatively low mass loss indicators are also characteristic of a three-layer coating obtained on the basis of a sol with an additive content of 0.5 %.

The influence of the fire test time on the mass loss of samples was studied. With increasing fire exposure time, the mass loss of samples increased. Given the general trend, the best fire protection was provided by a three-layer coating, because even after 10 minutes of fire exposure, the samples retained more than half of their initial mass.

In the range of SHMP concentrations of 0.1–0.3 % for a single-layer coating, a slight increase in mass loss was observed, which can be explained by the insufficient fire-retardant properties of the coating with such a thickness.

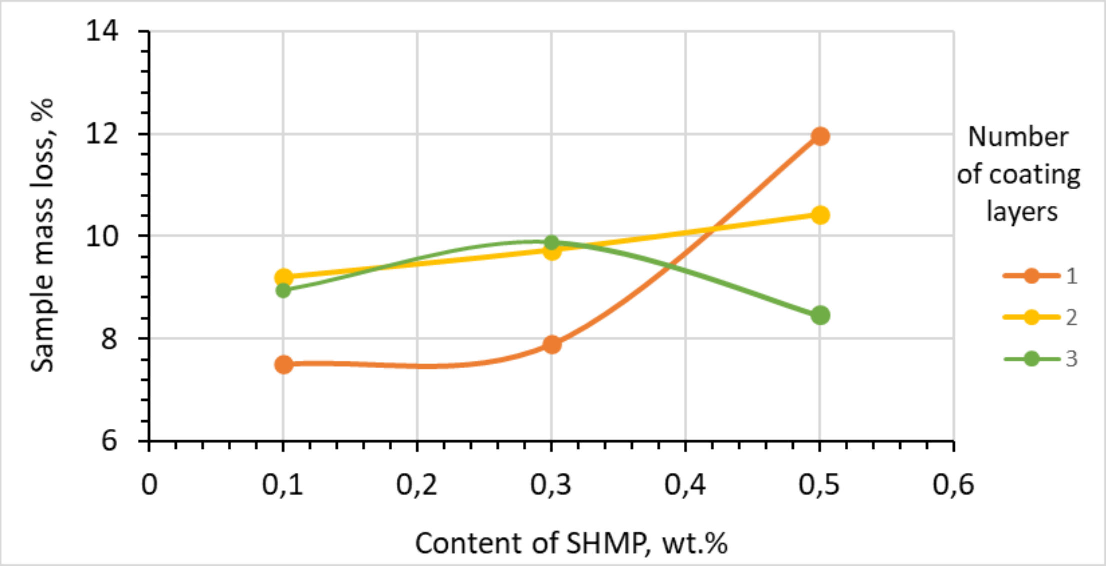

Fig. 7. The effect of sodium hexametaphosphate content on the change in mass loss of samples during fire tests for 2 min

For coatings applied in two and three layers, the trend described above was maintained throughout the fire test time. At a SHMP content of 0.3 %, the mass loss of samples was minimal. At 0.5 % of the additive, the mass loss became greater.

7. Study of the effect of sodium hexametaphosphate on the fire resistance of extruded polystyrene foam

Tabl. 2 shows the results of fire tests for extruded polystyrene foam samples.

Tabl. 2. Fire test results for extruded polystyrene foam samples

№	SHMP content, %	Number of coating layers	Sample mass loss, %	Ignition time, s	Note
1	Untreated sample		-	3	actively burned with the formation of burning drops
2	0.1	1	-	4	burned without the formation of burning droplets
3		2	-	8	
4		3	2.5	5	did not support combustion
5	0.3	1	1.57	-	did not burn
6		2	2.97	-	
7		3	-	7	burned without the formation of burning droplets
8	0.5	1	-	6	
9		2	-	5	
10		3	-	4	

As in the case of the study of the fire-retardant properties of a coating of a similar composition on a wood surface, the data in Tabl. 2 indicate the best fire-retardant performance of extruded polystyrene foam for compositions with a SHMP content of 0.1–0.3 %. Samples coated with compositions with a higher concentration of the component supported combustion, but a significant problem accompanying the combustion of polystyrene foam was eliminated – the formation of burning drops.

8. Discussion of the results of the study of the influence of sodium hexametaphosphate on the fire-retardant efficiency of coatings based on it

The dependence of the survival time of silicic acid sols on the content of sodium hexametaphosphate used as a modifier had a nonlinear U-shaped character with a clearly pronounced minimum at 0.3 % SHMP (Fig. 2).

This trend may be associated with electrical interactions that affect the stability of the sol and determine the degree of electrostatic repulsion between particles. The value of the ζ-potential, which reflects the difference in electric potentials between solid particles and the solution, serves as the main indicator of this repulsion. At high values of the ζ-potential, the colloidal system remains stably dispersed, preventing particle aggregation.

The decrease in the survival time of the sol in the range of 0.01–0.3 % with increasing additive content can probably be interpreted as an insufficient amount of hexametaphosphate to create an effective and uniform coating on the surface of colloidal particles. That is, some areas remain uncharged or insufficiently charged and are the cause of easy adhesion of particles, since the repulsive forces between them are insufficient to prevent them from coming closer together.

At the point of 0.3 %, a decrease in the ζ-potential can be observed due to the compression of the double electric layer, which leads to a decrease in electrostatic stabilization and an increase in the tendency to aggregation, respectively, a minimum survival time is observed.

In the concentration range of 0.3–1 %, it is likely that a more complete overlap of the particle surface with anions occurs, which contributes to the formation of a more stable Stern layer. But to a greater extent, an additional stabilization mechanism begins to manifest itself – the steric effect, i.e., HMF ions create a kind of physical barrier on the surface of the particles, which prevents their coagulation.

Such assumptions about the presence of two different mechanisms of formation of fire-retardant coatings in two different ranges of GMF content are confirmed by the results of infrared spectroscopy of raw silica gels. The smallest value of the ratio of the intensity of the absorption band at 1050 cm^{-1}, which corresponds to the vibrations of siloxane bonds, to its half-width, was observed at a SHMP content of 0.3 % (Fig. 6), which correlates well with the results of the study of rheological properties (Fig. 1–2). The linear mechanism of polycondensation is realized at an additive content of less than 0.3 %, which contributes to the formation of elastic coatings that are well held on the surface of the material. At values exceeding this indicator, network polycondensation probably occurs, which is characterized by the presence of clathrates – closed or semi-closed cavities formed by the spatial structure of silica, where water and other polycondensation products can be retained. A probable confirmation of this fact can also be an increase in the intensity of absorption bands in the IR spectra corresponding to hydroxyl groups, which may belong to adsorbed water molecules. The shape of the infrared spectra for heat-treated silica gels also confirms the fact of the presence of a linear polycondensation process at a GMP content of less than 0.3% and a reticular one above this value.

The hypothesis put forward is also confirmed by the results of fire tests. The smallest mass losses of wood samples were observed in the range of phosphorus-containing component content of 0.1–0.3 % (Tabl. 1), which indicates a linear mechanism of polycondensation. The results of studies of the influence of fire exposure time on mass losses of samples showed that the best fire-protective properties are provided by a three-layer coating (Fig. 8). The relatively short time intervals for reaching the maximum temperature at a content of 0.5 % may indicate the heterogeneity of the coating structure, i.e. a network mechanism of polycondensation.

If we assume that in the concentration range >0.3 %, there is already a network polycondensation, which contributes to the formation of less homogeneous coatings, then it is multilayering that can compensate for this disadvantage. Increasing the number of coating layers allows you to cover areas of the material where the coating has a loose structure, or is absent altogether (Fig. 7).

For extruded polystyrene foam, the best fire-retardant properties were shown by coatings obtained on the basis of compositions with the same SHMP content as in the case of wood (Tabl. 2). The reason that the samples did not burn (0.3 %) or did not support combustion (0.1 %) is the homogeneous structure of the coating, which does not crack when exposed to fire, and accordingly prevents the formation of point ignition of the foam.

Therefore, the silica-containing composition modified with 0.3% sodium hexametaphosphate can potentially be considered as a flame retardant for both natural (wood) and synthetic (expanded polystyrene) polymers.

Further research will be aimed at optimizing the composition by investigating and comparing the effects of other phosphorus-containing components on the flame-retardant properties of coatings on the surface of finishing building materials.

9. Conclusions

1. The effect of sodium hexametaphosphate on the gelation processes in silicic acid sols was investigated. It was found that the dependence of the survival time of the compositions on the additive content has a nonlinear U-shaped character with a minimum at a content of 0.3 %, which may be a transition point between two processes that are different in nature. According to infrared spectra, a linear mechanism of polycondensation was confirmed at a content of less than 0.3 % and a network mechanism at a content of more than 0.3 %.

2. It was found that a coating based on silicic acid sol modified with a sodium hexametaphosphate solution (at a 0.1–0.3 % additive content) provides optimal fire-retardant characteristics for wood, transferring the material to the “flammable” group.

The use of the developed coatings with GMF additives allows preventing the formation of burning drops (at a 0.1 % additive content) and even preventing the ignition of extruded polystyrene foam under conditions of optimal additive content (0.3 %).

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ДОСЛІДЖЕННЯ ВПЛИВУ НАТРІЙ ГЕКСАМЕТАФОСФАТУ НА ВЛАСТИВОСТІ КРЕМНЕЗЕМВМІСНОГО ВОГНЕЗАХИСНОГО ПОКРИТТЯ ДЛЯ БУДІВЕЛЬНИХ МАТЕРІАЛІВ

Розроблено склад силікофосфатної композиції, призначеної для вогнезахисту будівельних матеріалів. Як вихідні компоненти використовували розчини рідкого скла, оцтової кислоти та натрій гексаметафосфату. Досліджено вплив вмісту фосфоровмісної добавки на реологічні властивості золів кремнієвої кислоти. Методом спектрофотометрії встановлено, що час прихованої коагуляції в усьому діапазоні досліджуваного вмісту натрій гексаметафосфату становить ~20 хвилин. Зафіксовано найвищі значення оптичної густини для золю з умістом добавки 0,3 %. Розглянуто імовірність впливу електростатичних та стеричних ефектів, що залежать від концентрації фосфоровмісної добавки, на стійкість золю. Припущено, що мінімальне значення живучості золю при 0,3 % добавки пов'язано зі зниженням ζ-потенціалу та стисненням подвійного електричного шару. Результатами інфрачервоної спектроскопії підтверджено висунуту гіпотезу про два різні механізми поліконденсації в різних інтервалах вмісту гексаметафосфату. При вмісті нижче 0,3 % відзначено лінійний механізм поліконденсації, вище 0,3 % – сітчастий. Проведено вогневі випробування зразків деревини та екструдованого пінополістиролу, вкритих композиціями досліджуваного складу. Найкращі вогнезахисні властивості зафіксовано для систем з умістом натрій гексаметафосфату 0,1–0,3 %. Обробка зразків деревини дозволила перевести матеріал до групи «важкозаймисті», втрати маси зразків становили менше 10 %. Зразки екструдованого пінополістиролу не підтримували горіння при вмісті добавки 0,1 % або не горіли зовсім при вмісті 0,3 %, втрати маси становили менше 3 %. Було оцінено вплив кількості шарів покриття на ефективність його вогнезахисної дії: для деревини в інтервалі концентрацій гексаметафосфату 0,1–0,3 % найбільш термостійкими були тришарові покриття, для екструдованого пінополістиролу при вмісті 0,3 % – одно- та двошарові.

Ключові слова: вогнезахисні кремнеземвмісні покриття, натрій гексаметафосфат, будівельні матеріали, термостійкість, вогнестійкість, пінополістирол

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