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ESTABLISHING THE PATTERNS OF CHANGE IN THE FIRE RESISTANCE OF TENT FABRIC DURING TREATMENT WITH POWDER PAINT

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This study investigates the process that forms a fire-resistant coating based on polyester powder paint on tent fabric. The task addressed is to enable the fire resistance of tent fabric when treated with a coating based on polyester powder paint. This is important as the production of fire-resistant materials for construction is a relevant task.

It has been proven that under the influence of a burner flame on a sample of tent fabric treated with a powder coating based on polyester paint, a heat-insulating layer of foam coke of about 4 mm was formed on the surface within 15 s. However, the absence of foam coke was found in some places. A layer of foam coke with a length of more than 50 mm and a width of 20 ÷ 30 formed on the surface of a sample of tent fabric treated with a mixture of polyester powder paint and an intumescent system, while the height of the swelling exceeds 10 mm. This refers the tent fabric to flame-retardant materials as no burning or smoldering was recorded during the temperature exposure, and the temperature did not exceed 100°C.

Studies have shown that the obtained thermogravimetric indicators make it possible to establish the rate of thermal decomposition of the coating at certain temperatures and show a qualitative assessment of thermal effects and thermal destruction of materials, which is characterized by mass loss. Thus, endothermic processes for powder polyester paint begin when 210–290°C is reached with a subsequent intense mass loss of about 70%; when an intumescent system is added, the endothermic effects shift to the region of about 300–340°C with a mass loss of less than 56%. Thus, there is reason to argue about the possibility of effectively designing operationally stable biocomposites for construction

Keywords: tent fabric, polyester powder paint, intumescent system, fireproof coating, foam coke

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1. Introduction

Modular blocks made of textile products are easily erected buildings that use durable tarpaulin (tent fabric) to design frame structures, which is an alternative to capital construction. They are characterized by the rapid erection of structures that have a wide variety of shapes and resistance to adverse weather conditions (rain, snow, wind) as special water-repellent treatment makes the textile product resistant to moisture and precipitation. However, the main material for the manufacture of tarpaulin is natural plant raw materials based on flax and cotton fibers, which do not withstand thermal effects and are capable of ignition and spread of flame. Therefore, there is a need to design effective fire-retardant materials.

Thus, aqueous solutions of salt flame retardants are ineffective because under the influence of fluctuations in temperature and humidity fields they are washed out of the materials onto the surface and, given that the structures of modular buildings are not rigid, are subject to vibration and fall off the surface. In addition, flame retardants themselves are not environmentally friendly. Fire retardant coatings based on inorganic binders, where sodium liquid glass, Portland cement, alumina cement, aluminosilicate binders are used as a binder and contain bound water. During heating, the process of water evaporation and the formation of a ceramic phase on the surface of the textile product occurs, which blocks the transfer of heat to the surface of the material. However, such coatings have a large temperature coefficient of linear expansion and low adhesion strength, which makes them ineffective. A promising area is the design of weather-resistant, effective, and safe reactive coatings for such materials that are capable of forming a heat-resistant thermal insulation layer of foam coke under the influence of high temperature.

Therefore, research aimed at designing a fire-retardant coating, identifying the number of components, as well as defining its effect on the combustion process of a textile product.

2. Literature review and problem statement

Study [1] argues that the modifications are aimed at improving the performance parameters, using natural substances, moving away from synthetic materials, and improving ergonomics. To achieve this goal, various methods of fiber production are used, as well as adding substances, including nanomaterials, to the structure or surface of a certain material. In the case of fire-resistant fabrics, efforts are being made to reduce weight and eliminate harmful chemicals (for example, polycyclic aromatic hydrocarbons (PAHs)), as well as to design smart materials with sensors. However, further development is needed not only of the materials themselves but also of cleaning and decontamination methods that could make it possible to maintain the devised fire resistance parameters.

The authors of [2] noted that with the increase in sharp fluctuations in temperature and humidity, as well as the increase in the risk of fires caused by global climate change, the development of multifunctional textile materials is relevant. In addition, they combine moisture regulation and fire protection, which has become crucial for ensuring human health and safety. In the cited paper, the hydrophobic modification of calcium alginate (CA) fibers was successfully carried out using wet spinning technology combined with impregnation modification process. After surface modification with fluorocarbon (FC) resin, the width coverage angle (WCA) of CA-FC fibers was increased from $32 \pm 0.5°$ to $120.5 \pm 1°$, which successfully switched from hydrophilicity to hydrophobicity of natural polysaccharide fibers. In addition, the inherent flame-retardant properties of FC resin synergistically enhanced the flame-retardant performance of CA fibers. Using wettability gradient, a multifunctional protective fabric with unidirectional water conductivity and flame resistance was designed by combining hydrophobically modified CA-FC fibers with unmodified CA fibers. The wettability gradient between the hydrophilic side of CA and the hydrophobic side of FC provided the opportunity to achieve rapid unidirectional water transport while maintaining excellent fire-resistant properties; however, no optimal solutions for use have been identified.

In [3] it is noted that the flammability suppression of natural, synthetic, and blended textiles with a single treatment is a challenging task due to the different properties and chemical composition of the fibers. Intumescent surface treatments that promote the formation of char can be applied in the form of a polyelectrolyte complex (PEC) containing nitrogen and phosphorus compounds that prevent combustion in both the condensed and gas phases. Poly(allylamine hydrochloride) (PAH) and poly(sodium phosphate) (PSP) contain PEC, which reduces the flammability of cotton, polyester, and polyester/cotton (PECO). The inclusion of melamine makes each substrate self-extinguishing. It is observed that the decomposition of PEC differs between substrates, with gas phase decomposition being more prevalent on polyester and heterocyclization occurring on cellulose. Quantitatively, the flammability of cotton is reduced more than that of polyester, but significant improvements in char yield, heat release, and volatiles release are observed for all fabric types. This water-based coating is quickly applied in two steps for fire protection. The results demonstrate the versatility of PEC coatings as an environmentally friendly fire protection for various chemicals.

In [4], a fully bio-derived phosphorylated furan-based flame retardant (FAP) was synthesized via the Schiff reaction from furan compounds (furfural and furfurylamine). To evaluate the application scope and flame-retardant performance of FAP, cotton fabrics and nonwovens (PLA) were selected as biomass-based representatives from natural and synthetic fibrous materials, respectively. The results of thermogravimetric analysis (TGA) revealed that the residual char of C-FAP-3 and P-FAP-3 was 39.7% (267.6% increase) and 16.7% (215.1% increase), respectively, higher than that of the control cotton (10.8%) and PLA nonwoven (5.3%). The results of cone tests showed that the peak heat release rate (PHRR) and total heat release (THR) values of C-FAP-3 were sharply reduced by 69.4% and 37.8%, respectively. P-FAP-3 also showed a significant decrease in PHRR, indicating the high fire resistance of C-FAP-3 and P-FAP-3. In particular, due to the increase in flame retardants, as well as the final results on the Limiting Oxygen Index (LOI) and the Plastics, Coatings, Films and Glass Impact Tester (VBT) of the fabrics, it is found that the control cotton fabrics are more likely to achieve better flame-retardant effects than PLA. But it is not indicated how the degree of reduction in thermal resistance would be affected by the humid environment.

Paper [5] provides a brief overview of flame-retardant textiles, highlights the role of textiles in fire protection, and presents the key drivers of the flame-retardant textile market. It also focuses on the influence of textile parameters on the performance of flame-retardant fabrics, the behavior of fibers under heat, including examples of natural and synthetic fibers, heat-resistant and intrinsic flame-retardant fibers. It also discusses flame retardant finishing of textiles, illustrating the classification of flame retardants, their mechanism of action and durability; the surface coating methods used. In addition, the section provides an overview of some applications of flame-retardant textiles, their performance requirements, and recent developments in their production, such as firefighter protective clothing, and upholstered furniture. As well as textiles used in vehicles such as cars, aircraft, and marine vehicles. However, no flammability testing standards are presented for these applications.

The study reported in [6] demonstrates the applicability of composite materials based on basalt fiber reinforced polymers (BFRP) in thermal protection. Basalt fibers are produced from natural, environmentally friendly sources, and have mechanical characteristics comparable to commercial glass fibers. In addition to mechanical strength, BFRPs have excellent chemical and thermal resistance. Basalt fibers generally have higher thermal resistance than their competitors, glass fibers. The thermal resistance of basalt fibers is due to the volcanic origin of the raw material (basalt gabbro). To test the fire resistance of the materials, mono- and hybrid composite plates were made from different types of basalt reinforcing structures and epoxy resin. Surface treatment with silane coupling agents significantly improved the mechanical and thermomechanical properties of BFRP by up to 70%. Three-point bending tests were conducted to determine the bending properties of the composite samples, and their fire resistance was evaluated using a horizontal burning test and a novel jet burning test using infrared thermal imaging. The higher fiber content in the hybrid laminates reduced the linear burning rate by 8%, and the maximum surface temperature was approximately 80°C lower. However, it is not indicated how the composites are operated.

In [7], the tensile strength and flame-retardant properties of cotton dyed with eco-friendly plant extracts were investigated. The study investigated antibacterial dyed cotton fabrics in detail from the perspective of improved flame-retardant properties due to eco-friendly plant extracts for cotton fabrics while simultaneously analyzing their tensile strength. Mangosteen-dyed cotton fabrics showed better results compared to untreated cotton fabrics of 140 g/m^2 and 240 g/m^2, with tensile strengths of 237.87 kg/cm^2, 288.69 kg/cm^2, and 238.38 kg/cm^2, 288.47 kg/cm^2. Flame reaction studies showed that the burning time increased from 35 s for untreated plain cotton fabric of 140 g/m^2 to 50 s and 45 s for fabrics dyed with mangosteen and borage. Accordingly, the burning rate changed from 320 mm/min for untreated plain cotton fabrics of 140 g/m^2 to 290 mm/min and 300 mm/min for fabrics dyed with mangosteen and borage, respectively. The results of the limited oxygen index (LOI) tests showed that fabrics dyed with borage showed a slight increase in LOI values up to 20 compared to other treated samples. However, its effect on improving the overall environmental profile was not observed.

The main focus of work [8] was to thoroughly investigate the improvement of thermal resistance/insulation characteristics of flame-retardant cotton fabrics treated with milk casein, a biomacromolecule-based flame retardant. Milk casein (a phosphorus-containing protein) was applied as a green flame-retardant finishing material to cotton fabrics using aqueous solutions using an industrially applicable method. To evaluate the thermal protection characteristics, samples of cotton fabric treated with single-layer casein were exposed to a radiant heat source at a specific radiant heat flux density according to the standard test method ISO 6942-B. It was found that the transmitted heat flux density and heat transfer coefficient shifted to lower values for the cotton fabric samples treated with casein compared to the untreated cotton fabric, but no improvement was observed, indicating improved thermal protection.

The study reported in [9] successfully scaled up the preparation of a flame-retardant material based on P/N-rich cotton meal (PmC), a functional material in which phosphate groups are chemically introduced into the natural components of cotton meal. An innovative mechanical grinding method purifies the solid biomass for application to the surface of cotton fibers. PmC is integrated with cotton fibers through a flame-retardant treatment process, forming hydrogen and covalent bonds between PmC and cotton fibers, thereby achieving long-term wash resistance for flame retardant cotton fibers. The limiting oxygen index (LOI) of 110 g/L cotton fibers treated with PmC reaches 38.4%, and the damage length is only 50 mm. Cone calorimetric tests showed that the total heat release (THR) and peak heat release rate (pHRR) of cotton fibers treated with PmC were reduced by 38.7% and 82.9%, respectively. Comprehensive analysis using TG-IR, XPS residual carbon, SEM-EDS also revealed that PmC mainly exerts its flame-retardant effect. It is not known whether it affects the condensed phase of cotton fabrics.

In study [10], solutions of aloe vera, bean seeds, and tea leaves were applied to knitted fabrics of 100% cotton, 100% viscose, and 100% para-aramid as natural nitrogen-based flame retardants. The limiting oxygen index (LOI) values of the treated fabrics increased from 18 for untreated cotton to a maximum of 26.3 for cotton treated with aloe vera. This increase was observed from 18 for untreated viscose to 24.5 for viscose treated with tea leaf extract and from 28 for untreated para-aramid to 39.2 for para-aramid treated with aloe vera. The treated fabrics maintained their flame-retardant properties with LOI > 21 even after the fifth wash, although their performance decreased with repeated washing. Flammability tests at 45° also showed a significant reduction in the burning rate, confirming the effectiveness of the treatments. X-ray diffraction showed that compared to the untreated sample, the crystalline particles of the treated fabrics were slightly modified. SEM analysis demonstrated that the surface of the treated fibers was quite rough due to the small amount of coated natural flame retardant, while FT-IR spectroscopy data showed that the natural flame-retardant components were grafted onto the treated fibers. Overall, by improving the flame-retardant properties of textiles, the natural nitrogen-based flame-retardant material was able to overcome the shortcomings of environmentally friendly flame retardants and make them suitable for use as nitrogen-based flame-retardant textiles.

Calcium phosphate, as noted in [11], is an effective flame retardant for cotton but its production needs to be scaled up using cheaper and more environmentally friendly raw materials. Recycling chicken bones as a source of calcium phosphate offers a sustainable solution, reducing waste and increasing the fire resistance of the fabric. The extraction process involves the digestion of chicken bones with hydrochloric acid, precipitation of calcium phosphate using ammonia, and then filtering and drying the product. The extracted calcium phosphate was applied to the cotton fabric using a coating process. Different treatment conditions, such as flame-retardant dosage, pH of the treatment solution, ammonia concentration, temperature and curing time, were evaluated using the Taguchi L9 experimental design to optimize the process. The flame-retardant properties were evaluated using a vertical burning test, which showed that the treated fabrics had lower flammability than the untreated ones. The burning time increased from 42 seconds for the untreated fabric to 64 seconds for the treated fabric, demonstrating the effectiveness of the calcium phosphate treatment, but no tests were specified to evaluate the strength of the panels.

In study [12], a novel nanoparticle flame retardant material was synthesized by the Mannich reaction and applied in combination with hydrolyzed silica sol KH-570 to finish polyester fabrics. In contrast to traditional methods, an innovative synthesis route was used that eliminates complex post-processing steps, allowing the reaction mixture to be directly used as a flame-retardant material. By varying the number of laying cycles, different addition levels were achieved, which greatly simplified the preparation process. The successful synthesis of the flame-retardant material and its effective deposition on the fabric were confirmed by FT-IR, XPS, and SEM-EDS analyses. Performance evaluations demonstrated a significant increase in the limiting oxygen index from 21.2% to 32.5%, while vertical combustion tests confirmed self-extinguishing behavior without leakage. Cone calorimetry analysis revealed a significant decrease in the peak heat release rate from 139.84 kW/m^2 to 67.04 kW/m^2. The study demonstrates that the system works through a synergistic mechanism: the nanoparticle components contribute to the quenching of radicals in the gas phase and the catalytic formation of char, while the Si component increases the mechanical strength of the char layer. This combination results in highly effective fire resistance and droplet protection characteristics. However, no role in their fire resistance has been observed.

Thus, we have established from the literature [4, 5, 9–12] that the treatment of building structures from textile natural fibers is able to provide their protection from thermal effects during operation. However, the parameters that guarantee the effectiveness of protection against high-temperature action required for their manufacture have not been established. Therefore, determining the fire protection characteristics of textile materials for construction and the influence on the pyrolysis process of natural fibers of the coating components has necessitated the need for research in this area.

3. The aim and objectives of the study

The purpose of our work is to determine the conditions for the formation of a fire-retardant coating of tent fabric based on powder polyester paint. This could make it possible to substantiate the directions of application of these products in construction.

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

– to identify the features of change in the thermal stability of powder polyester paint when adding an intumescent system based on dispersed substances;

– to establish features in the suppression of the combustion of tent fabric by a fire-retardant mixture of powder polyester paint and intumescent system under thermal action.

4. The study materials and methods

4. 1. Object and hypothesis of the research

The object of our study is the process of designing a fire-resistant coating based on polyester powder paint for tent fabric. The scientific hypothesis is the formation of a fire-resistant coating from a mixture of polyester powder paint and dispersed substances of an intumescent coating on the surface of the tent fabric.

In the process of the study, it was assumed that the process of designing a fire-resistant tent fabric is constant under the influence of external conditions. It was simplified that the temperature, humidity, and pressure of the tent fabric processing process do not change.

4. 2. Tested materials used in the experiment

To study the possibility of fire protection of textile material, tent fabric (50% cotton/50% jute) produced by TC “Textile Contact” (Ukraine), measuring 220 × 170 mm, with a thickness of about 1.5 mm and a density of 89...90 g/m^3 (Fig. 1) was used.

Fig. 1. Fabric sample for testing

To form a coating on the surface of the tent fabric, Etika polyester paint (made in Turkey) was used, which is a highly dispersed powder consisting of polyester resins, hardeners, pigments, film-forming substances, and other additives. When hardened, they react with each other, forming a durable coating. Powder paint is a combustible material with an ignition temperature when exposed to an open flame from 270 to 435°C. To increase its fire resistance, it was proposed to add to its composition a mixture of dispersed substances that are part of the intumescent coating, namely, ammonium polyphosphate, pentaerythritol and melamine. Polyester paint was mixed in a 1:1 ratio with a mixture of dispersed substances of the intumescent coating and tested for thermal resistance. It was also applied to the fabric and thermal polymerization was carried out at a temperature of about 190°C for 60 s to form a fire-retardant coating. The total paint consumption was about 280 g/m^2. After cooling the sample, a layer of polyester paint was applied to the surface of the fireproof coating to secure the coating.

After the formed coating was aged for 14 days, the samples were tested for fire protection efficiency and fire resistance.

4. 3. Methodology for determining the properties of samples

The study of thermal changes in powder polyester paint when adding an intumescent system based on dispersed substances was carried out by identification using the method of thermogravimetric analysis, and the features of fire protection of tent fabric by interaction with a high-temperature flame under thermal action.

Thermogravimetric analysis was carried out on a Linseis STA 1400 derivatograph (Germany) according to [13]. In order to determine the temperature range at which thermal destruction of materials occurs most intensively, a thermogravimetric study of destruction processes under dynamic mode was carried out. For this purpose, a research station manufactured by TA Instruments (USA) with a TGA (thermogravimetric analysis) module TGA Q50 was used. Samples weighing 10 mg were heated in an air atmosphere from 20 to 700°C at a rate of 10°C/min.

The determination of the protective efficiency of a mixture of polyester paint and intumescent system when treating tent fabric was carried out according to the working methodology from [14], the essence of which was to experimentally determine the characteristics of burning materials under the influence of flame in controlled laboratory conditions. For testing, a test rig was used in which a test sample of textile material (220 × 170 mm in size) was fixed and a gas burner with a flame height of 40 mm was connected. During the tests, the duration of residual flame combustion, material burnout, surface flash propagation, and the average length of the charred area were recorded.

The essence of the test method for experimental determination of the flammability index of a fire-resistant sample of tent fabric is to expose the sample, which is located in the installation, to the flame of a burner or radiation panel with specified parameters [15]. With the subsequent determination of the parameters of ignition and flame propagation through the material, the determination of the thermal coefficient of the installation, measurement of the maximum temperature of the combustion products and the time of its achievement were carried out experimentally. The ignition time and the passage of the flame through the surface areas, the length of the burnt part of the sample, as well as the final combustion after removing the burner for 600 s were also determined and the value of the dimensionless flammability index was calculated.

5. Results of determining the conditions of fire protection of tent fabric with powder paint

5. 1. Experimental studies on the thermal stability of powder polyester paint with the addition of an intumescent system

To establish the thermal change of powder polyester paint, thermogravimetric analysis was performed. Graphic images of thermogravimetric analysis are shown in Fig. 2, 3.

In powder paint samples at temperatures below 100°C, endothermic processes occurred, which is due to the evaporation of water without the destruction of the components of the powder paint, at which mass loss occurs. The temperature at which intensive destruction of the components begins, that is, rapid mass loss of the samples is observed, is 210–290°C. In particular, in the powder paint sample, along with the endothermic processes of pyrolysis (elimination of volatile products), exothermic oxidation processes occurred, as evidenced by the thermal effects curve (DTA) in the region of the first peak of the differential temperature curve (DTG). Namely, the presence of a noticeable exoeffect starting from a temperature of 290°C, on which a smaller endoeffect with a maximum in the region of 330°C is superimposed. From the thermogram (Fig. 2), the stage of decomposition processes at a certain temperature was assessed, as well as the relative mass loss upon heating (Table 1).

For a powder paint sample, the stage of intensive mass loss up to temperatures of 350°C, which may be due to the formation of volatile combustion products, is characteristic, as is a slower stage (at higher temperatures when mass loss has already reached 60–70%), which is due to the burning out of the carbonized residue and is characterized by an exothermic effect.

Table 1

Results of powder paint sample tests

Mass loss (%) at temperature						
200°C	300°C	400°C	500°C	600°C	700°C	800°C
7.0	20.0	31.5	40.0	50.0	69.1	75.5
Temperature (°C) of mass loss						
10%	20%	30%	40%	50%	68%	75%
280	300	400	450	550	650	800
Residue at 800°C: 30.5%						
Characteristics of maximum peaks of differential curve DTG (T_{max}, °C/mass loss rate, % min^{-1})						
Interval	50–800°C					
Peak	200/7.2	290/19	350/23.0	490/30.5		700/69.1
Characteristics of effects DTA (T_{max}, °C/effect type)						
Interval	100–800°C					
Peak	210/endo	290/endo		400/exo		

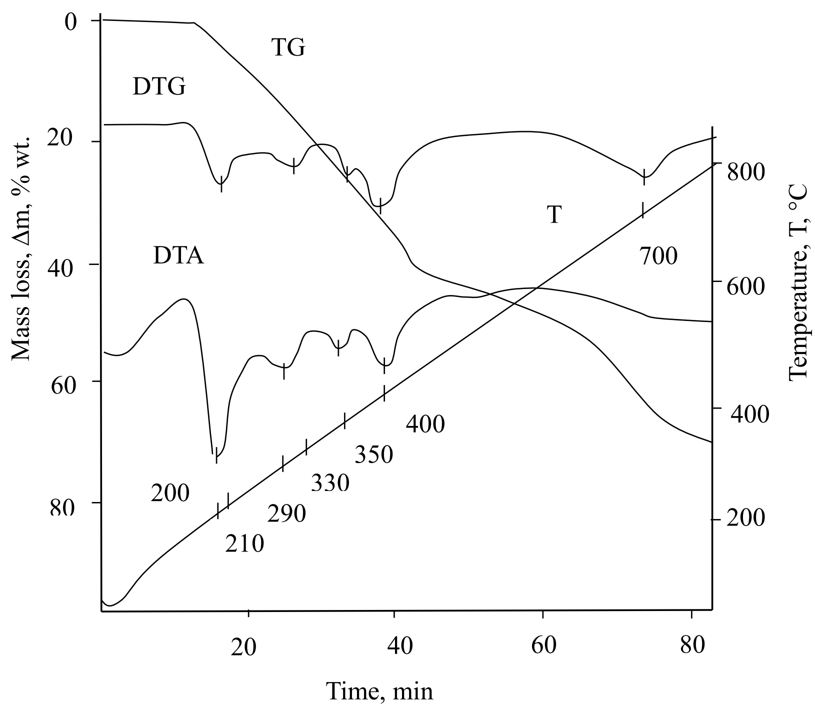

Fig. 2. Thermogravimetric analysis curves for a sample of polyester powder paint

A separate analysis is required by the nature of curves from thermogravimetric analysis of a sample of a mixture of powder polyester paint and intumescent system. For them, the temperature of water evaporation and the beginning of decomposition of components and the release of chemically bound water are noted, the maximum destruction rate is observed (285°C). The magnitude of this rate also does not change significantly (the maximum deviations of the corresponding DTG curves are close in magnitude). Instead, the destruction processes at the second stage largely depend on the nature of the fire-retardant composition: as its fire-retardant action slows down, the mass loss slows down. Accordingly, the appearance of the DTA indicators changes, namely, the height decreases and the width of the peaks that characterize the course of endothermic transformations increases, as a result of which the process of thermo-oxidative destruction is recorded at higher temperatures, that is, the process ends at a temperature of 700°C. From the thermograms, the temperatures at which mass loss is achieved were determined and the stages of decomposition processes were estimated, as well as the relative mass loss upon heating to 700°C (Table 2).

Table 2

Results from investigating a sample mixture of polyester powder paint and intumescent system

Mass loss (%) at temperature								
100°C	200°C	300°C	400°C	500°C	600°C	700°C		
3.5	5.5	15.0	38.0	46.5	54.5	55.0		
Temperature (°C) of mass loss								
10%	20%	30%	40%	50%				
280	310	340	430	540				
Residue at 700°C: 45.0%								
Peak maxima characteristics DTG (T_{max}, °C / mass loss rate, % min^{-1})								
Interval	40–640°C							
Peak	70/0.5	230/0.7	320/4.1	340/3.8	460–565/0.8			
Characteristics of effects DTA (T_{max}, °C / effect type)								
Interval	210–670°C							
Peak	325/ exo	345/ endo	415/ exo	460/ exo	565/ exo			

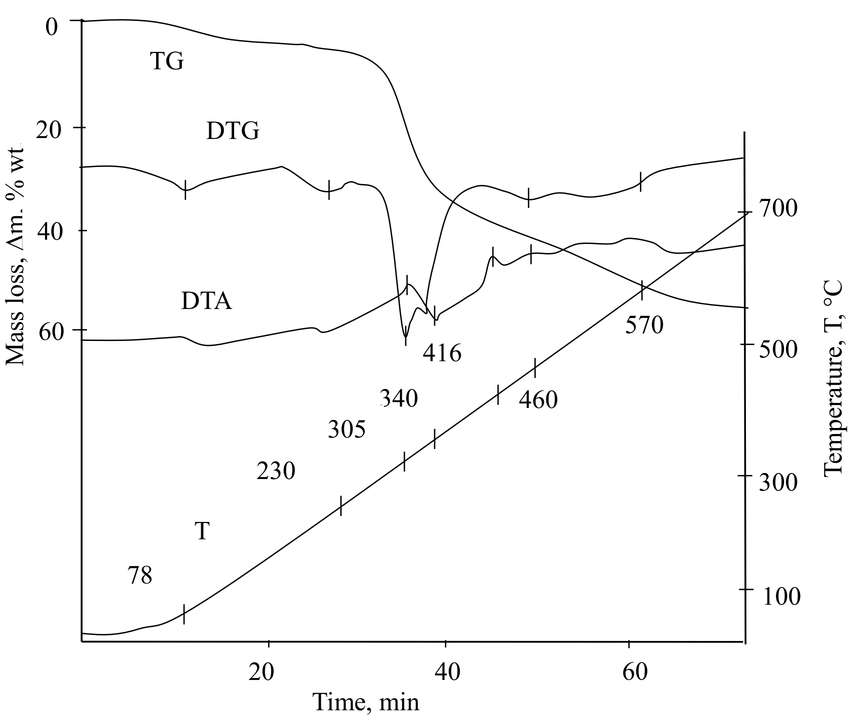

Fig. 3. Thermogravimetric analysis curves for a sample mixture of polyester powder paint and intumescent system

Thus, the obtained thermogravimetric indicators make it possible to establish the rate of thermal decomposition of the coating at certain temperatures and show a qualitative assessment of thermal effects and thermal destruction of materials, which is characterized by mass loss. Thus, endothermic processes for powder polyester paint begin when reaching 210÷290°C with subsequent intensive mass loss of about 70%, and when adding an intumescent system, endothermic effects shift to the region of about 300–340°C with mass loss of less than 56%.

5. 2. Results of studies on the effectiveness of fire protection of tent fabric

The flammability of the fabric treated with a mixture of powder polyester paint and intumescent system was determined by interaction with a high-temperature flame under the action of a burner that simulates a low-calorie source. The results of studies on the ignition of a sample tent fabric are shown in Fig. 4.

At the first stage of the studies, tent fabric was tested, which was treated with a powder coating based on polyester paint. As a result of the studies, it was found that during the action of the burner flame on the fabric for 15 s, a thermally insulating layer of foam coke of about 4 mm was formed on the surface, but in some places it was absent.

Fig. 5 shows the results of studies to determine the protective effectiveness of a mixture of polyester paint and an intumescent system when treating tent fabric.

Thus, on the surface of the tent fabric sample treated with a mixture of powder polyester paint and intumescent system, a layer of foam coke with a length of more than 50 mm and a width of 20 ÷ 30 formed; the swelling height was more than 10 mm.

Fig. 6 and Table 3 show the process of experimental determination of the flammability index of a fire-resistant tent fabric sample.

Studies have shown (Fig. 6) that the fire-resistant sample of tent fabric belongs to flame-retardant materials because during temperature exposure no burning or smoldering was recorded, and the temperature did not exceed 100°C.

During testing of tent fabric samples, it was found that the sample treated with polyester powder paint caught fire on 36 s, the flame spread to the fourth section within 130 s, the burning length of the sample was 120 mm, and the flammability index was 12.1. In contrast, the sample fire-protected with a mixture of polyester powder paint and intumescent system did not catch fire, the flame did not spread over the surface, the maximum temperature of the flue gases was 99°C, and the flammability index was 0. The above results make it possible to determine the ratio of intumescent substances and polymers in these coatings and their required quantity.

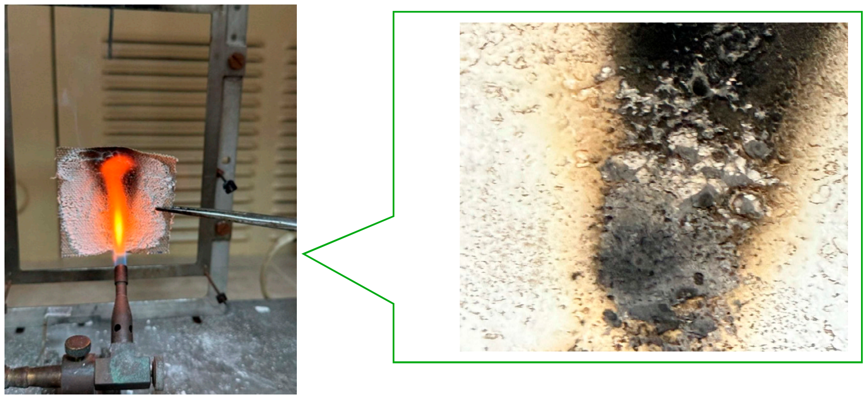

Fig. 4. Results of research into the swelling process of powder paint on the surface of tent fabric

a *b* *c*

Fig. 5. Results of investigating the ignition process and flame spread of a sample of tent fabric treated with a mixture of polyester powder paint and an intumescent system: *a* – effect of flame on the sample; *b* – swelling of the coating; *c* – protective layer of foam coke

a *b* *c*

Fig. 6. Results of testing the process of determining the flammability index of a fire-resistant sample of tent fabric: *a* – thermal effect on the sample; *b* – swelling of the sample; *c* – formation of a protective layer of foam coke

6. Discussion of results based on investigating the patterns of fire protection of tent fabric with powder paint

A comparison of studies on determining the fire protection of tent fabric treated with powder paint (Fig. 4–6, Table 3) makes it possible to show that a sample of tent fabric treated with a mixture of powder polyester paint and an intumescent system does not support combustion and the spread of flame along the surface. It was found that under the influence of a burner flame on a sample of fire-resistant tent fabric for 15 s, a thermally insulating layer of foam coke was formed on the surface, which indicates the inhibition of combustion processes.

Table 1 demonstrates that during the tests of the tent fabric samples it was found that the sample treated with polyester powder paint caught fire for 36 s, the flame spread to the fourth section within 130 s, the burning length of the sample was 120 mm, the flammability index was 12.1. In contrast, the sample, fire-protected with a mixture of polyester powder paint and intumescent system, did not catch fire, the flame spread over the surface did not occur, the maximum temperature of the flue gases was 99°C, and the flammability index was 0. This demonstrates the feasibility of the results regarding the inhibition of the ignition process of tent fabric protected by an intumescent coating. That is, the inherent formation of foam coke on the surface of the fabric, which prevents its ignition because under the influence of the high temperature of the flame, the destruction of the coating begins. Namely, the decomposition of hydrocarbon catalysts unfolds, which induce the decomposition of pentaerythritol and melamine to form non-flammable gases that inhibit redox reactions and lead to swelling of paint components under thermal action [16].

Table 3

Time of passage of the flame front through control points

Tent fabric sample	*T* of flue gases, °C		Ignition time, s	Time of passage of flame front through sample sections, s									Time to reach max. flue gas temperature, s	Burning length of sample, mm	Flammability index
	T_1	T_{max}		1	2	3	4	5	6	7	8	9			
Treated with polyester powder paint	65	314	–	36	28	20	46	–	–	–	–	–	536	120	12.1
Fireproofed with mixture of polyester powder paint and intumescent system	68	99	–	–	–	–	–	–	–	–	–	–	600	0	0

Evaluation of the results of our studies on determining the flammability index of a fire-resistant sample of tent fabric showed that the fire-resistant sample of tent fabric belongs to flame-resistant materials. During the temperature exposure, no burning and smoldering was recorded, and the temperature did not exceed 100°C. Thus, on the surface of the sample of tent fabric, treated with a mixture of powder polyester paint and intumescent system, a layer of foam coke with a length of more than 50 mm and a width of 20 ÷ 30 formed, and the height of the swelling is more than 10 mm. This confirms the mechanism of the protective coating, which makes it possible to identify it by high-temperature exposure [17].

Therefore, taking into account the results of the analytical review [2, 3, 5–7], which describe the process of protective coating formation on the surface of tent fabric, this article reveals the mechanism of the formation of a heat-insulating layer of foam coke using an intumescent system, which is well-known.

However, in contrast to the results reported in [18] regarding the mechanism of fire protection of tent fabric, it is possible to state the following:

– the main process of inhibiting thermal action to the tent fabric is the creation of a significant amount of a layer of foam coke, which prevents the penetration of thermal action because inorganic coatings under the influence of temperature form ceramic phases and give off water;

– the process of protection with an intumescent coating is essential, which makes it possible to create an elastic film on the surface of the tent fabric, which exhibits stability during operation and under the influence of thermal action to form a layer of foam coke.

The interpretation of our results from determining fire resistance, confirmed by experiments, ensures their justification during operation, which has certain priorities for the data of experimental studies. However, these experimental data on determining the fire resistance of tent fabric are limited because the use of polyester powder paint requires an increased amount.

In addition, the insignificant thermal resistance of polyester powder paint to high temperatures does not yield the required number of results and limits its application in this direction. Among the disadvantages is the fact that the obtained experimental results have the most reliable data in the graphical form of representation. However, thanks to our studies, the role of the intumescent system in their operation is made possible. The subsequent direction of work on the development of fire protection makes it possible to study the optimal composition of the coating.

7. Conclusions

1. Our studies have shown that the obtained thermogravimetric indicators make it possible to establish the rate of thermal decomposition of the coating at certain temperatures and show a qualitative assessment of thermal effects and thermal destruction of materials, characterized by mass loss. Thus, endothermic processes for powder polyester paint begin when 210–290°C is reached with a subsequent intensive mass loss of about 70%, and when an intumescent system is added, endothermic effects shift to the region of about 300–340°C with a mass loss of less than 56%.

2. As a result of the tests, it was found that under the influence of a burner flame on a sample of tent fabric treated with a powder coating of polyester paint, a layer of foam coke of about 4 mm was formed on the surface within 15 s. However, in some places, the absence of foam coke was detected. On the surface of the tent fabric sample treated with a mixture of polyester powder paint and intumescent system, a layer of foam coke with a length of more than 50 mm and a width of 20 ÷ 30 mm was formed, and the height of the swelling was more than 10 mm. This associates the tent fabric with flame-resistant materials as during the temperature exposure no burning and smoldering was recorded, and the temperature did not exceed 100°C.

During the tests of the tent fabric samples to determine the flammability index, it was found that the sample treated with polyester powder paint caught fire in 36 s. This led to the spread of the flame to the fourth section within 130 s, the burning length of the sample was 120 mm, the flammability index was 12.1. In contrast, the sample, fire-protected with a mixture of polyester powder paint and an intumescent system, did not ignite, the flame did not spread over the surface, the maximum temperature of the flue gases was 99°C, and the flammability index was 0.

The above results make it possible to determine the ratio of intumescent substances and polymers in these coatings and their required quantity.

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.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

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Authors' contributions

Yuriy Tsapko: Conceptualization, Methodology, Formal analysis, Writing – review & editing, Supervision. **Oleksiy Tsapko:** Conceptualization, Investigation, Data analysis, Writing – original draft. **Oksana Berdnyk:** Investigation, Data analysis, Formal analysis, Writing – original draft. **Ruslan Likhniovsky:** Methodology, Data curation, Validation. **Tetiana Nehrii:** Resources, Validation, Funding acquisition. **Oksana Kasianova:** Resources, Supervision, Validation. **Stanislav Skarlat:** Validation, Funding acquisition, Visualization. **Anduij Lyn:** Funding acquisition, Validation, Visualization. **Yarema Velykyi:** Investigation, Resources, Funding acquisition. **Roman Konanets:** Resources, Supervision, Validation.

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