An issue related to using concrete for building structures is to ensure their stability and durability during operation within wide limits. Therefore, the object of research was the change in the properties of concrete in case of fire and its protection when applied with a reactive coating capable of forming a foam coke layer under the influence of high temperature on the coating. It has been proven that in the process of thermal action on the fire-resistant coating, the process of heat insulation of concrete involves the formation of soot-like products on the surface of the material. Thus, under the influence of the flame of the burner, a temperature arose on the surface of the sample, which led to the swelling of the coating by more than 18 mm. The measured temperature on the surface of the concrete sample under the layer of foam coke was no more than 140 °C, which indicates the formation of a fire barrier. In this regard, modeling of the process of heat transfer through the formed layer of foam coke in the process of its protection with a reactive coating was carried out and dependence was established, which makes it possible to estimate the coefficients of temperature conductivity and thermal conductivity during high-temperature action. According to the experimental data and the established dependences, the coefficient of temperature conductivity and heat conductivity of foam coke was calculated, which is $9.17\cdot10^{-7}$ m²/s and 0.17 W/(m·K). The assessment of the maximum possible penetration of fire through the layer of foam coke was carried out. A temperature was formed on the surface of the sample, which significantly exceeded the temperature of the destruction of concrete, and on the surface of concrete under the coating it did not reach 250 °C. So, there are reasons to assert the possibility of targeted regulation of concrete fire protection processes by using reactive coatings capable of forming a protective layer on the surface of the material that inhibits the rate of heat transfer

Keywords: protective means, structural concrete, thermal destruction of the surface, fire protection of concrete, swelling of the coating

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DETERMINING PATTERNS IN THE FORMATION OF AN INSULATION LAYER OF FOAM COKE WHEN PROTECTING CONCRETE AGAINST FIRE BY REACTIVE COATING

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1. Introduction

Concrete and reinforced concrete structures are the basis of civil and industrial construction due to their non-flammability and relatively low thermal conductivity, which show good resistance to fire. But they cannot resist fire indefinitely, because when heated above 250÷300 °C, the structure of cement stone and concrete is disturbed due to deformations of hydrated products of cement stone and non-hydrated cement grains. At 500...600 °C, there is decomposition of hydrate formations and dehydration of $Ca(OH)_2$, which further reduces the strength of cement stone, and when the temperature rises to 900 °C, cement stone loses its strength and breaks down.

Understanding the mechanism of flame action on concrete, measures have been developed to protect against its destructive effect, in particular, avoiding excessive heating of the structure. This is achieved by creating an insulating (protective) surface layer of non-combustible material, which can be based on a layer of concrete itself, plaster material, or special systems with different plates.

Fire protection can be reduced to the use of coatings of the facing and heat-insulating type, the fire-protective effect of which consists in the thermophysical properties of the protection material used, as well as in the use of reactive-type coatings, which swell under thermal action, forming a heat-insulating coke layer on the protected surface.

The quality of reactive paints is usually determined by the main characteristics, such as the fire-retardant efficiency of the material and the manufacturability of application and restoration. In addition, resistance to the effects of the external environment, the warranty service life of the coating and its operating conditions are important.

The application of lightweight materials with heat-insulating properties or the use of board and sheet heat-insulating materials (plasterboard and gypsum-fiber sheets) for external structures leads to significant material costs and an increase in the volume of the structure. In addition, the mechanism of protection of concrete by reactive coatings against the effect of fire temperature has not been sufficiently studied, which makes it impossible to obtain objective information about the nature of the processes that occur during operation, as well as fire protection efficiency. The lack of theoretical ideas about the influence of flame retardants on the fire resistance of concrete, the role of which belongs to reactive coatings, significantly limits the scope and prospects of using these materials.

Therefore, research aimed at determining the patterns of inhibition of the process of fire heat transfer to a concrete structure in the process of protection with a reactive coating is relevant.

2. Literature review and problem statement

Work [1] notes that concrete has good strength and durability; however, it suffers from spalling and a significant reduction in strength when exposed to flame. The study was aimed at increasing the fire resistance of concrete by using two different methods: fiber reinforcement or application of a fire-retardant coating. For this, mixtures of steel fiber (SF), glass fiber (GF), polypropylene fiber (PPF) were made in the amount of 0.5÷2 % of the mass of cement; in addition to the mixture prepared with a 15 mm layer of refractory covering material and the control mixture. All mixtures were exposed to elevated temperatures of 200÷800 °C and their physical and mechanical properties were evaluated. According to the test results, both techniques were effective in increasing the fire resistance of concrete mixtures. The maximum residual compressive and flexural strengths were obtained for the mixture containing 0.5 % GF, which were 117 % and 145 % higher than the control mixture at 800 °C, respectively. In addition, the refractory-coated concrete showed up to 76 % and 113 % higher compressive and flexural strengths, respectively, compared to the control mix. It has been found that the addition of fibers during the concrete production process is a more desirable and cost-effective approach to increase fire resistance. However, for the existing concrete structure, the use of a fireproof coating is the only option and can comparatively increase the fire resistance.

In [2], an attempt was made to reveal the fire resistance of a full-scale self-insulating multilayer wall made of textile reinforced concrete (TRC). For this, the fire resistance limit and the characteristics of the destruction of the samples were investigated, namely: the type of cement material, the thickness of the base layer, the thickness of the TRC panels, the type of reinforcing, polypropylene (PP) fiber, as well as the type of fireproof coating. For Portland cement-based specimens with 16 mm TRC panels and a 90 mm core layer, the fire resistance limit was 203 min, which is much more than the requirement for partitions and non-bearing walls. And it was also established that samples based on high-alumina cement can maintain their integrity in a flame, although their thermal insulation is slightly weaker than that based on Portland cement. In addition, the fire resistance of the samples can be improved by increasing the thickness of the base layer and TRC panels and applying fire-resistant coatings.

In article [3], authors reviewed some recent developments in the literature regarding the passive protection of concrete structures using intumescent coatings. Although spalling of concrete structures has long been recognized as a serious problem that can often lead to catastrophic infrastructure failure, the utility of intumescent pavement as a mitigation strategy is new and understudied. Therefore, in the last parts of the review, the authors tried to discuss different types of intumescent coatings, their methods of action and, in particular, their wider application from the point of view of protecting concrete elements from the harmful effects of strong or explosive splitting. As a conclusion, given that spalling of concrete components is a very serious problem, there is a need to formulate mitigation strategies with new means and methods. The use of an intumescent coating in this context appears to be a promising route but it seems to be still little explored.

In study [4], fire tests of four hollow steel tubular samples and twenty samples filled with concrete steel tubes (CFST) lasted 180÷240 min and were carried out according to the standard fire resistance curve ISO-834. At the same time, all samples were protected by an intumescent fire-resistant coating (IFC). A technical process for determining the IFC equivalent thermal conductivity applied to CFST columns was proposed. A verified Finite Element Analysis (FEA) model was built to predict the temperature field of an IFC protected CFST section and the effect of CFST section size on the temperature field was studied. The intumescent coating was found to be able to reliably perform together with the CFST specimens without general spalling during a sustained fire exposure of up to 240 min. The temperature rise of the CFST column steel tube can be significantly slowed down by the effective insulation of the IFC together with the heat absorption of the concrete core. The main factors affecting the temperature rise of an IFC-protected CFST section during a fire are the core concrete, the dry film thickness (DFT) of the IFC and the diameter of the section. However, the conducted experimental tests allow checking the results calculated according to the mathematical model.

The swelling coating is able to provide effective protection against fire simultaneously with practicality and aesthetics [5]. In the cited study, experiments are first conducted on the expansion performance and thermophysical properties to obtain the basic parameters at different temperatures. A model of the thermal response of a concrete-filled steel tubular (CFST) structure under the protection of an intumescent pavement during a fire is then established. Finally, the effects of initial thickness, expansion rate, intrapore emissivity, and heat of response on temperature are discussed in detail based on experimental data and a thermal response model. The results of the study can provide guidance for swelling coating as well as fire protection design.

The fire resistance of prestressed concrete (PC) structures is seriously degraded due to the sensitivity of these structures and significant high temperature damage [6]. To this end, very limited research has been conducted on the effect of swelling fire-retardant coating (IFC) on the fire resistance of PC structures. Under combined thermal loading and external loading, the appearance, thermal response, deflection, prestress variation, and fire resistance of structures at high temperature are measured and compared. The effect of IFC on the fire resistance of a PC box beam has been previously investigated. The test results showed that IFC can effectively reduce spalling, fracture and cracking of concrete, effectively prevent the concrete structure from reaching very high temperature, and also greatly reduce the deflection of PC structure at high temperature and effectively protect the prestressing of the structure. The fire resistance of PC structures can be effectively improved with IFC. However, it is found that the fire resistance of a PC box girder with high bending stiffness can be determined by its ultimate bearing capacity rather than its ultimate high-temperature deflection.

In paper [7], adhesion strength and interfacial connection between coatings and substrates, coating methods and their characteristics, as well as coating on different substrates are considered. Adequate reactions between the precursor material and the alkaline activator are essential to achieve strong adhesive strength of the coatings on the substrates and to obtain compatible shrinkage with the substrates. Additives to the precursor materials increase the fire resistance, either by controlling the expansion of the coating or by forming swelling phases. It has been proven that the increased thickness of AAM coatings, which is largely determined by the technique of formation, is a significant factor in increasing their fire resistance and corrosion resistance. However, issues related to the ability to preserve color and its stability remained unresolved.

Thus, it was established that during the operation of concrete structures, they may be affected by high flame temperature, and therefore they need effective fire protection. In addition, the parameters that ensure the resistance of concrete to thermal action have not been determined. The limited explanation and description of the process of fire protection of concrete, the neglect of the use of organic substances for the formation of heat-insulating coatings lead to ineffective use of protective means. Therefore, establishing the parameters of concrete resistance to thermal breakdown and the effect of coatings on this process necessitated conducting research in this area.

3. The aim and objectives of the study

The purpose of our work is to establish the regularities of the formation of a fire-resistant coating on the surface of a concrete structure. This makes it possible to substantiate the directions of expansion of the scope of application of concrete products.

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

– to conduct modeling of thermal conductivity during the formation of a swollen coating layer under the influence of fire on the surface of concrete;

– to establish the features of thermal conductivity inhibition through the swollen layer of foam coke under thermal action.

4. Research materials and methods

4. 1. Object and research hypothesis

The object of this study is the heat-insulating properties of the foam coke layer formed during thermal action on the reactive coating. The scientific hypothesis assumes a change in the heat-insulating properties of a foam coke layer during thermal exposure to a fire-resistant concrete sample.

4. 2. Researched materials used in the experiment

A 100×100×100 mm concrete sample was used for the research (Fig. 1). To study the effectiveness of fire protection of concrete, the surface was coated with “FireWall Wood” coating (produced in Ukraine), which can swell under the influence of high temperatures [8]. The coating consumption was about 360.0 g/m^2.

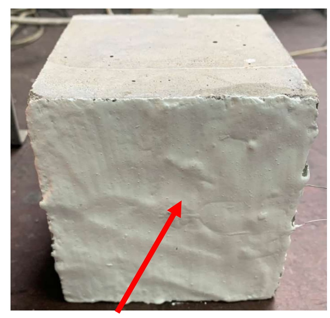


Fig. 1. Concrete samples for research

After drying to a constant weight of the sample of fire-resistant concrete, tests of the treated concrete samples were carried out for the effectiveness of protection.

4. 3. Methodology for determining fire protection indicators of concrete with a reactive coating

Special equipment with a gas burner simulating a high-temperature source was used to conduct research on fire protection of concrete with a reactive coating (Fig. 2).

Determination of the fire-resistant properties of concrete with a fire-resistant coating was carried out by evaluating the characteristics of heat transfer through a layer of foam coke formed under the action of a flame under controlled laboratory conditions. A thermocouple was placed in the coated concrete sample and secured under the coating. For temperature measurements, a Chromel-Alumel (TXA) thermocouple was used, which is designed for temperature measurement in the range of up to +1000 °C, the diameter of the electrode wire is 0.2 mm, the diameter of the joint is 0.6 mm. The thermocouple was connected to a computer via an ADAM-4017, which uses a microprocessor-controlled 16-bit sigma-delta analog-to-digital converter to convert voltage into digital data that is translated into temperature. At the request of the host computer, the module sends data to the host computer via the standard RS-485 interface. A test rig was used to carry out the research, in which a concrete sample was fixed. Surface testing was performed using a Sturm gas burner with piezo trigger ignition (5015-KL-02), manufactured in China. The tests were carried out for 600 seconds, for this the burner was installed in a vertical position with a flame height of 100 mm. After that, the burner was brought to a sample of fire-resistant concrete, subjected to thermal action and the temperature under the coating was measured.

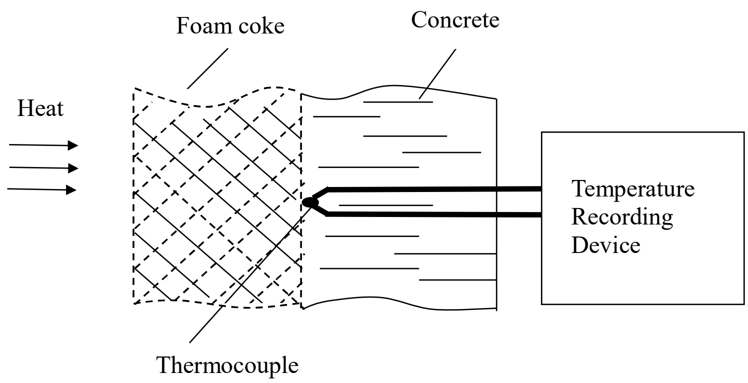


Fig. 2. A device for studying the thermal conductivity of fire-resistant concrete

The criterion for determining the thermal conductivity of fire-resistant concrete during thermal action is the inhibition of thermal conductivity under the coating, which does not exceed the temperature of the beginning of the destruction of concrete (250 °C). At the same time, the swelling of the coating in the form of a layer between the heating medium and the starting material is fixed. Using the measured temperature values, the heat-insulating properties of the foam coke layer were calculated.

To model the process of thermal conductivity of the swollen coating layer during thermal action on the example of fire-resistant concrete, the basic principles of mathematical physics were used [9].

5. Results of determining the thermophysical characteristics of foam coke under thermal influence on a fire-resistant concrete sample

5. 1. Modeling of thermophysical characteristics for a layer of foam coke on the surface of fire-resistant concrete during thermal action

Under the influence of the heat flow on the samples of the fire-resistant concrete sample, the process of formation of a heat-resistant heat-insulating layer of foam coke takes place, which inhibits the transfer of heat to the concrete.

Taking into account that the determination of the thermophysical characteristics of foam coke is related to the measurement of temperature, starting from the thickness of the coating from 0.5÷1 mm, therefore, to establish the thermophysical characteristics of the heat-insulating layer of foam coke formed on the surface of concrete, a method is proposed for solving the problem of thermal conductivity for the system of two unlimited plates with different thermophysical properties [10]. At the initial moment of time, the outer surface of the coating is heated to the decomposition temperature with the formation of a layer of foam coke, and the temperature distribution passes through the swollen layer until the critical temperature of the concrete surface is reached.

To this end, consider two areas (Fig. 3):

1 – foam coke zone, $0<x\leq R$ (R – foam coke formation coordinate, m);

2 – concrete sample, $R\leq x\leq\infty$.

Differential equations of heat transfer on the surface of a fireproof concrete sample represent a system of two unlimited plates and take the form [11]:

– for foam coke:

$$a_1\frac{\partial^2 T_1(x,\tau)}{\partial x^2}-\frac{\partial T_1(x,\tau)}{\partial\tau}=0,\ (\tau>0;\ 0<x<R),\quad (1)$$

– for concrete sample:

$$a_2\frac{\partial^2 T_2(x,\tau)}{\partial x^2}-\frac{\partial T_2(x,\tau)}{\partial\tau}=0,\ (\tau>0;\ R<x<\infty),\quad (2)$$

under initial and boundary conditions:

$$T_1(x,0)=T_2(x,0)=0,\quad (3)$$

$$T_1(R,\tau)=T_2(R,\tau)=0,\quad (4)$$

$$\lambda_1\frac{\partial T_1(x,\tau)}{\partial x}=\lambda_2\frac{\partial T_2(x,\tau)}{\partial x},\quad (5)$$

$$T_1(x,\tau)=T_c=\text{const},\quad (6)$$

$$T_2(\infty,\tau)=0,\quad (7)$$

where a_1, a_2 are the coefficients of temperature conductivity of foam coke and concrete;

λ_1, λ_2 – heat conductivity coefficients of foam coke and concrete;

R is the thickness of foam coke.

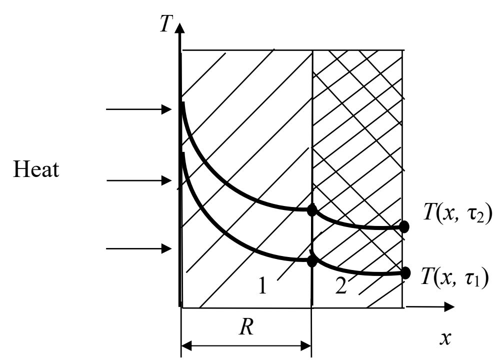


Fig. 3. Scheme of the fire protection process of a concrete sample: 1 – foam coke; 2 – concrete

The solutions to equations (1) and (2) with initial and boundary conditions (3) to (7) are given in [12] as dependences:

$$\theta_1=\frac{T_1(x,\tau)}{T_c}=erfc\frac{x}{2\sqrt{a_1\cdot\tau}}-$$
$$-h\sum_{n=1}^{\infty}h^{n-1}\left[erfc\frac{2n\cdot R-x}{2\sqrt{a_1\cdot\tau}}-erfc\frac{2n\cdot R+x}{2\sqrt{a_1\cdot\tau}}\right];\quad (8)$$

$$\theta_2=\frac{T_2(x,\tau)}{T_c}=$$
$$=\frac{2K_\varepsilon}{1+K_\varepsilon}\sum_{n=1}^{\infty}l^{n-1}\cdot erfc\left[\frac{x-R+(2n-1)\cdot K_a^{-1/2}\cdot R}{2\sqrt{a_2\cdot\tau}}\right],\quad (9)$$

where:

$$K_\varepsilon=\frac{\lambda_1}{\sqrt{a_1}}\cdot\frac{\sqrt{a_2}}{\lambda_2};\quad h=\frac{1-K_\varepsilon}{1+K_\varepsilon};\quad K_a^{-1/2}=\sqrt{\frac{a_2}{a_1}}.$$

Thus, equation (8) characterizes the temperature in the swollen layer of foam coke, and measuring its thickness is a difficult task. For this, equation (9) is considered, which depicts the temperature distribution in the concrete sample and which depends on the temperature in the foam coke. Taking into account that the convergence of the series (9) increases, the temperature value is sufficiently accurately described by the first term [13]:

$$\theta_2 = \frac{2K_\varepsilon}{1+K_\varepsilon} erfc\left[\frac{x - R\cdot K_a^{-1/2}\cdot R}{2\sqrt{a_2\cdot\tau}}\right]. \tag{10}$$

Taking into account the above, the thermophysical characteristics of foam coke can be determined according to the following scheme.

It is assumed that at the point $x=R$ at the time τ_1 the temperature will be:

$$\theta_{x=R} = \frac{2K_\varepsilon}{1+K_\varepsilon} erfc\frac{R}{2\sqrt{a_1\cdot\tau_1}}, \tag{11}$$

and at the point $x>R$ the temperature is reached during time τ_2 and will be:

$$\theta_{x>R} = \frac{2K_\varepsilon}{1+K_\varepsilon} erfc\left(\frac{x - R + K_a^{-1/2}\cdot R}{2\sqrt{a_2\cdot\tau_2}}\right). \tag{12}$$

Therefore, at the moment of time τ_1, the relative temperature at the point $x=R$ is θ_1, and at the moment of time it is $\tau_2 - \theta_2$, respectively.

The ratio of these temperatures will have the following expression:

$$\beta = \left(\frac{\theta_2}{\theta_1}\right)_{|x=R} = \frac{erfc\left(\xi^{-1}\cdot k\right)}{erfc\ k}, \tag{13}$$

where:

$$\xi = \sqrt{\frac{\tau_2}{\tau_1}}; \tag{14}$$

$$k = \frac{R}{2\sqrt{a_1\cdot\tau_1}}. \tag{15}$$

For this case, the calculation equation for the coefficient of temperature conductivity of foam coke will be calculated from equation (15) and take the form:

$$a_1 = \frac{R^2}{4k^2\cdot\tau_1}, \tag{16}$$

and for the coefficient of heat conductivity of foam coke, by substituting (16) into (11), we obtain:

$$\lambda_1 = \frac{\theta_1\cdot B\cdot R}{2k\cdot\sqrt{\tau_1}\cdot A}, \tag{17}$$

where

$$B = \frac{\lambda_2}{\sqrt{a_2}}, \tag{18}$$

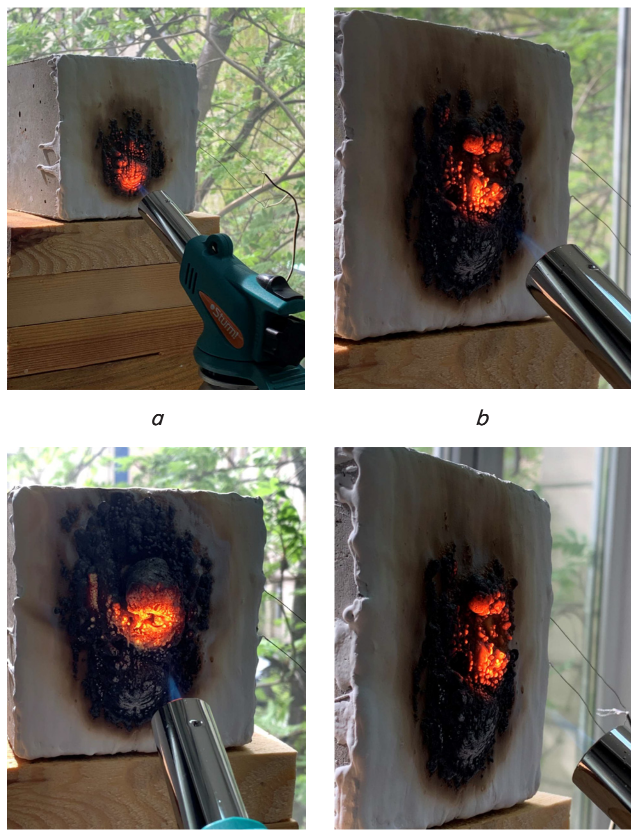
$$A = 2erfc\ k - \theta_1. \tag{19}$$

To determine k, it is necessary to determine the values of β and ξ based on experimental data, by which to determine *erfc k*, which corresponds to k [14]. Then the coefficients of temperature conductivity and heat conductivity of foam coke are calculated based on the obtained values.

As a summary, calculation dependences (16) and (17) were constructed, which allow obtaining thermophysical characteristics for the layer of the swollen coating based on the experimental values of the temperature difference and known values of temperature conductivity and heat conductivity of concrete.

5. 2. Results of determining the temperature on the concrete surface under the swollen coating layer under thermal influence

In order to elucidate the fire protection efficiency of the coating for the concrete sample, studies were conducted on its thermal conductivity under the action of a burner simulating a fire source. The results of research on determining heat transfer by a fire-resistant concrete sample are shown in Fig. 4, 5.



a *b* *c* *d*

Fig. 4. Determining the heat-insulating properties of the fire-resistant concrete sample under the action of the burner: *a* – fixing the concrete sample; *b* – setting the height of the flame; *c* – temperature effect on the concrete sample; *d* – swelling of the fireproof coating

In the process of thermal action of the burner on a sample of fire-resistant concrete, the coating began to swell and the temperature under the coating increased slightly. Later, during the thermal exposure, it was established that the coating swelled within 400 seconds, forming a dense layer of foam coke, which was about 18 mm.

Fig. 5. Foam coke layer formation

The results of research to experimentally determine the temperature under the coating on the surface of concrete in the form of an experimental curve are shown in Fig. 6.

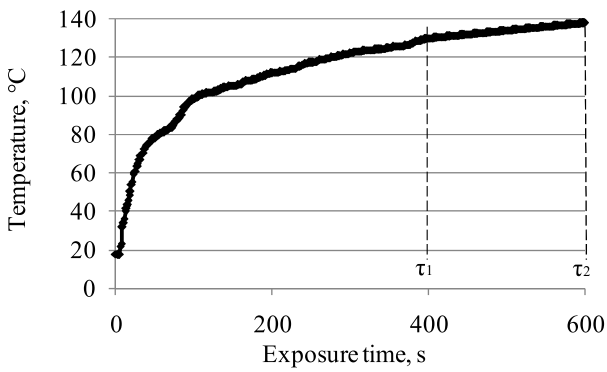


Fig. 6. The temperature value on the concrete surface under the foam coke layer when exposed to the burner flame

Studies have shown that under the influence of the flame of the burner, a sample of fire-resistant concrete withstood the thermal impact. Under the influence of high temperature, the coating swelled for 400 seconds, the temperature on the concrete surface under the coating did not exceed 140 °C.

Thermophysical characteristics of concrete are defined in [15]; the results are given in Table 1, taking into account that the power of the gas burner is about 1650 W, and the flame temperature of the gas burner is about 1300 °C [16]. Taking into account the results of temperature measurements (Fig. 6) and using the obtained dependences (16) and (17), the thermophysical properties of the swollen coating layer were determined. For this purpose, a period of time was selected when a layer of foam coke was formed under the action of a gas burner on the coating, Fig. 6. So, the coefficient of temperature conductivity of the swollen coating layer is $9.17\cdot10^{-7}$ m^2/s, and the coefficient of thermal conductivity is 0.17 W/(m·K), respectively.

Table 1

Thermophysical characteristics of concrete and foam coke

Material name	Thickness, mm	Insulation thermal-physical characteristics			
		Density ρ, kg/m^3	Temperature conductivity, m^2/s	Heat conductivity λ, W/(m·K)	Conditional body capacity, kJ/(kg·K)
Structural concrete	100	2,400	$0.75\cdot10^{-6}$	1.510	0.84
Foam coke	20	620	$9.17\cdot10^{-7}$	0.170	0.334

The results of studies on determining the thermophysical characteristics of the swollen coating layer of a fire-resistant concrete sample correspond to the properties of the heat-resistant layer of foam coke [17]. The absence of concrete destruction shows the resistance of the fire-resistant coating to the influence of high flame temperature and substantiates the effectiveness of the protection.

6. Discussion of results of studying the process of formation of a foam coke layer during the fire protection of concrete

When studying the process of fire protection of concrete with a reactive coating, as follows from our results (Table 1, Fig. 6), it is natural to inhibit the time of temperature transmission through the heat-insulating layer. This is due to the formation of a swollen layer of coke on the surface of fire-resistant concrete in the process of decomposition of flame retardants under the action of flame, which slows down the processes of heat transfer to concrete and its destruction.

It should be noted that the presence of a modified reactive coating leads to the formation of an elastic film on the surface of concrete, resistant to mechanical vibrations. Obviously, this mechanism of influence of the elastic film is the factor regulating the process, thanks to which the fire resistance of concrete is preserved. In this sense, it makes sense to interpret the results of the determination of the foam coke layer after the flame exposure to the coating, namely the amount of swelling of the coating sample during thermal exposure, since the coating layer reached a value of more than 18 mm, and the temperature on the reverse surface of the sample was no more than 140 °C. This indicates the formation of a temperature barrier, which can be identified by the method of thermal impact on the samples.

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

A comparison of experimental studies on the determination of thermal insulation of the coke layer in the process of fire protection of concrete and theoretical studies of thermal insulation with foam coke indicates inhibition of heat transfer processes since the temperature on the inverted surface under the action of the burner did not exceed 140 °C during the thermal effect of a gas burner with a temperature over 1300 °C for 600 s, and the coating layer reached a size of more than 18 mm (Fig. 5, 6).

This does not differ from the practical data, well known from works [1, 3, 5], the authors of which, by the way, also associate the effectiveness of fire protection with the formation of a foam coke layer under the influence of the burner flame. But, in contrast to the results of research reported in [6, 7, 18, 19], our data on the effect of the swelling coating on the process of retarding the transfer of temperature allow us to state the following:

– the main regulator of the process is not only isolation from the influence of air but also the formation of a significant amount of thermal insulation of the flame since individual fire-resistant coatings are destroyed under the influence of high temperature;

– a significant impact on the process of concrete protection during the application of a fire-resistant coating is carried out by the formation of a layer of coke from an elastic film on the surface of a polymer shell, resistant to destruction under the influence of product vibrations.

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

However, it is impossible not to note that the results of the determination (Fig. 5) indicate an ambiguous influence of the foam coke layer on temperature changes. This is manifested, first of all, in the inhibition of heat transfer to the surface of the concrete sample through the coating during thermal action. Such uncertainty imposes certain limitations on the use of our results, which can be interpreted as the disadvantages of this study, since the disadvantage of the formed swollen layer of the coating for fire-resistant concrete is the high temperature, which must be reduced much below the concrete's destruction temperature. The impossibility of removing the mentioned limitations within the framework of this study gives rise to a potentially interesting direction of further research. In particular, it can be focused on detecting the moment of time when the fall in fire-resistant properties and destruction of concrete under the influence of high temperature begins. Such a discovery will allow us to investigate the structural transformations of the elastic film of the coating, which begin to occur at this time, and to determine the input variables of the process that significantly affect the beginning of such a transformation.

7. Conclusions

1. Modeling of the process of heat transfer through the formed layer of foam coke during its protection with a reactive coating was carried out, and dependences were established that allow obtaining a change in the dynamics of heat transfer and determining the thermophysical properties of the layer of foam coke. According to the experimental data and the obtained dependences, the coefficient of temperature conductivity and heat conductivity of concrete was calculated, which is $9.17 \cdot 10^{-7}$ m^2/s and 0.17 W/(m·K), respectively, by forming a heat-insulating layer of foam coke.

2. Features of retarding the process of heat transfer to the material treated with a reactive coating are the formation of a heat-protective layer of foam coke on the surface of the concrete. Thus, a temperature was created on the surface of the sample that significantly exceeded the temperature of destruction of concrete, and on the surface of the concrete under the coating it did not exceed 140 °C.

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 presented work.

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