Methods of increasing the resistance of concrete to catastrophic failure in a fire

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Abstract. A characteristic feature of modern building industry is an increase in the construction of high-rise, technically complex and unique objects. A special role in ensuring the safety of objects of this kind is played by fire protection of load-bearing structures. The aim of this work was to review existing solutions aimed at increasing the fire resistance of reinforced concrete structures in order to ensure normative indicators. The research method is theoretical analysis. The issue of protecting reinforced concrete structures from brittle destruction of concrete in a fire is considered in detail. It has been established that a very effective way to maintain the integrity of a reinforced concrete structure during fire exposure is to modify the composition of concrete and control the structure in order to create a certain pore volume in concrete. The available data on the use of such methods are mainly empirical. The influence of qualitative and quantitative indicators of the additives used, the possibility of combining various methods to increase the fire resistance of concrete, modes of heating structures in a fire, and others are not sufficiently studied. These tasks seem relevant and require additional research.

1. Introduction
Fires caused serious material damage at all stages of the existence of mankind. Construction failures are the leading cause of death and fire damage. The most common building material in the construction of public, residential and industrial buildings is reinforced concrete. In order to reduce dead load, increase usable floor area by reducing the dimensions of structures and economic benefits, thin-shell concrete construction, as well as prefabricated hollow slabs, ribbed plates and thin-layer panels and slabs are often used in modern construction. Providing fire security is one of the main tasks in the construction (and reconstruction) of buildings and structures. The requirements for fire security are becoming more stringent and one of the important areas of scientific research is the study of methods that ensure the fire resistance of reinforced concrete structures when exposed to high fire temperatures.

The aim of this work was to review existing solutions, focused on increasing the fire resistance of reinforced concrete structures, from the point of view of controlling the composition and structure of the main material of the structure - concrete, identifying their advantages and disadvantages, as well as identifying areas for further research in this area.

2. Theoretical analysis
There are various ways to increase the fire resistance of reinforced concrete structures. Analysis of
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literary sources [1-4] made it possible to classify ways to increase the fire resistance of reinforced concrete structures as follows (Fig. 1).

Figure 1. Ways to increase the fire resistance of reinforced concrete structures.

Golovanov V.I., Pavlov V.V. and Pekhotikov A.V. showed that increasing the fire resistance of reinforced concrete structures by increasing the size of the cross section and the thickness of the protective concrete layer is impractical and often impossible due to the significant weighting of the structures [5].

One of the problems with the fire impact on a reinforced concrete structure is explosive spalling of concrete [6–9], which results in destruction of the protective concrete layer and exposure of working reinforcement. As a result, rapid reinforcement heating occurs and the structure prematurely loses its bearing capacity (Fig. 2). In the study of Roytman V.M. [6] it is shown that the protection of concrete from explosive spalling is a very effective way to increase the fire resistance of reinforced concrete structures. At the same time, some measures to protect against explosive spalling concrete allow only more rational use of fire resistance of structures, while others significantly increase it.

Figure 2. Explosive spalling of concrete (http://www.tehnobeton.ru/)
For example, the application of 30 mm thick flame retardants to reinforced concrete hollow core slabs with an actual fire resistance limit of REI 60 provides an increase in their fire resistance to REI 180. Fire retardant sprayed mineral materials with inorganic cement have a high force of adhesion to surfaces. The retardants are applied to the surface of structures mechanically (mix shotcreting process of almost any thickness, with a thickness of one layer not more than 15 mm). The thickness of the resulting coating can be from 10 to 60 mm, depending on the required fire resistance of the protected structure. The disadvantage of this type of coating is its low mechanical strength characteristics. The composition of such retardants includes binders, expanded aggregate, fiber materials, plastifying agents, etc. Their effectiveness increases with decreasing mass specific gravity. Plasters on expanded aggregate (with perlite and vermiculite) with an average density of 400–1000 kg/m³ have good fire retardant properties.

Another method of increasing the fire resistance of structures is flame retardant intumescent paints and coatings, which form a thin opaque layer on the surface to be protected. At a certain temperature, the bloating effect occurs, and the layer thickness can increase by 50-100 times as a result of the formation of gaseous agents under the influence of temperature. Paints are applied to the surface of structures with a thin layer up to 3 mm thick. At a temperature of 170-220 °C, the coating swells and forms a porous thermal insulating layer having low thermal conductivity. As a result, fast heating of the protected elements is prevented. Currently, a large number of fire retardant intumescent paints on various bases have been created for indoor use. The disadvantages of intumescent fire retardant coatings are: high cost, low durability and reliability, low alkali fastness, which is important when used for reinforced concrete structures. Therefore, their use for fire protection of reinforced concrete structures does not seem appropriate [1].

Large-scale application for fire protection of building structures is found in membrane fireproofing - large-sized sheet and plate sidings (gypsum fiber sheets, perlite plates, mineral wool boards, etc.). They can be hard and soft (rolled). Non-combustible slabs consist of an incombustible gypsum core with an average density of 800–1150 kg/m³, all planes of which, except the end edges, are lined with fireproof fiberglass. Fastening of large-sized sheets and plates on the surface of structures is carried out using metal fastening elements or special adhesive cements. False floor should also be attributed to the same fire protection method. The installation of false floor is associated with high labor costs, an increase in the cost of construction, and also reduces the architectural expressiveness of the interior of the building (for example, during the reconstruction or restoration of historic buildings). Fire-resistant false floor as structural and functional element is used to protect horizontal structures, mainly for structures of coatings and ceilings with beams, girders, structures and trusses [2]. Sometimes for fire protection of building structures are used heat insulating products using mineral binders, expanded vermiculite and perlite, mineral fiber. Fireproof boards based on expanded vermiculite and mineral binders are among the most effective means of increasing the fire resistance of building structures. Fireproof boards are used with an average density of 300 to 1,500 kg/m³ based on expanded vermiculite, perlite, expanded clay, asbestos, mineral wool, fiberglass, basalt fiber and other types of fillers. At the same time, the lining of reinforced concrete structures with fireproof plates and sheets significantly increases the labor costs of fabrication and the cost of the structure. A similar effect is exerted by the use of an external flame retardant layer using heat-resistant concrete. Particularly effective is the use of heat-resistant concrete with indicators of average density and thermal conductivity, which change with increasing temperature exposure. In addition, heat-resistant concrete must have increased strength and low deformability.

3. Discussion
Among the very effective methods of increasing the resistance of concrete to explosive spalling (and, in general, the fire resistance of the structure), various methods of modifying the composition and controlling the structure of concrete can be attributed. It is known that the critical temperature leading
to a decrease in the bearing capacity of concrete structures is 600 °C. However, the ambient temperature during a fire can reach higher values of 1200 °C or more. The mechanism of explosive spalling of concrete is well understood. With increasing temperature, the process of dehydration of the phases of the cement stone begins - hydrosilicates, hydroaluminates and hydrodieroferrites of calcium, portlandite. As a result, a large volume of steam accumulates in concrete (including the humidity of the concrete itself and a certain amount of physically bound water), which does not have a free exit to the surface of the structure. The reduction in strength is also facilitated by the failure of adhesion between the aggregate and the cement stone due to different coefficients of linear thermal expansion, and phase transitions of quartz (sand). In some cases, explosive spalling of concrete can occur within 5-10 minutes after the start of fire on the structure. Accordingly, possible tools to prevent this process are:

- limitation of thermal effects on the structure (methods discussed above);
- evaporative moisture limitation;
- increasing tensile strength of concrete;
- creation of conditions for the unimpeded removal of water vapor from the concrete body.

The use of special heat-resistant concretes for reinforced concrete structures of mass construction does not seem advisable in view of the fact that there is a certain set of technological limitations and a constraining economic factor. To increase the fire resistance of concrete, it is possible to include silica-containing (fine powder) mineral additives in its composition that bind calcium hydroxide formed during the hydration of clinker minerals of Portland cement. In studies of Ledenev A.A., Percev V.T., Zagoruiko T.V. issues of developing compositions of heat-resistant concrete were considered [3]. Portland cement of high class was used as a binder. The tasks of increasing the strength indices and decreasing the crack resistance of concrete were solved due to its micro-reinforcement with chrysotile asbestos, which are fine fibers. In order to reduce shrinkage from high temperatures, granular slag was used. An air-entraining admix was used to obtain porous heat-resistant concrete. Particular attention when choosing components is given to schungite, a characteristic property of which is the ability to swell during high-temperature exposure, to reduce the average density and thermal conductivity of a heat-resistant material.

Cracking in concrete, and, consequently, loss of load-bearing ability, can be prevented or its effect on the material properties can be reduced by the use of dispersively reinforced concrete. There are various types of dispersion-reinforced concrete, the main sign of classification of which is the type of fiber used (table 1).

In recent years, the development and use of steel fiber concrete is rapidly developing. Its high rates of strength, crack resistance and durability have been convincingly proved by studies carried out in many countries of the world. Steel fiber has a high average density (7850 kg/m³), high tensile strength (up to 600 MPa), high elastic modulus (2 · 10^5 MPa) [8]. There is also a need to assess the performance of steel fiber reinforced concrete in case of fire. An analysis of the literature showed that, despite a significant number of works performed in different countries (USA, Germany, France, India, South Korea, Singapore, Malaysia, Taiwan, China, Australia, Romania, Algeria, Greece, Iraq, etc.), this question has not been fully studied. This primarily relates to steel fiber concrete with a high-strength cement-sand matrix and high-strength steel fiber, which are used in thin-walled load-bearing structures, mainly working in tension and tension in bending. The fire resistance of steel fiber concrete, as well as its other physical, mechanical and operational characteristics, is greatly influenced by the composition and characteristics of the matrix, the type and characteristics of dispersed reinforcement, as well as the geometric characteristics of steel fiber concrete structures and the modes of temperature exposure. In the studies of Dorf V.A., Krasnovskiy R.O., Kapustin D.E., Sultygova P.S. It is shown that the fire resistance of steel fiber concrete is higher than that of ordinary concrete, especially in the temperature range up to 600 °C. At a temperature of 1000 °C and higher, both the degradation of the cement matrix and the temperature corrosion of steel fiber occur [13]. Therefore, to increase the fire resistance of steel fiber concrete at temperatures above
800 °C, it is necessary to change the composition of the cement matrix and increase the diameter of the fiber fibers or change the type of steel.

Table 1. The effect of dispersed concrete reinforcement on its fire resistance.

| №  | Types of dispersed reinforced concrete | Fiber type                                                                 | Functioning principle and result                                                                                                                                 |
|----|----------------------------------------|---------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------|
| 1  | Steel fiber concrete                   | Metal fibers: made of cold-drawn wire or sheet steel, with anchors in the form of bends, zigzag shape | Fiber increases the tensile strength of concrete and inhibits cracking at high temperatures. The fire resistance of steel fiber concrete is higher than that of ordinary concrete, especially in the temperature range up to 600 °C. The probability of explosive spalling decreases during elevated temperatures. |
| 2  | Mineral fiber reinforced concrete      | Fiberglass, basalt fiber, chrysotile fiber                                 | Mineral fiber stands temperature of 600 ... 800 °C, without undergoing changes, increases the tensile strength of concrete and reduces the probability of cracking, including with fire exposure. |
| 3  | Synthetic fiber reinforced concrete    | Synthetic fibers: polyethylene, polyester, polypropylene                   | When firing on a structure, synthetic fiber liquify (polypropylene at a temperature of about 170 °C), and then burns out, forming a system of open pores in concrete through which the pressure of superheated water vapor is released. The probability of catastrophic failure of concrete is reduced. |

Of the mineral fibers for dispersed concrete reinforcement, basalt, glass fiber, chrysotile fiber are most often used. These fibers have a low average density of ~ 2600 kg/m³, a tensile strength of (1...3,5)·10³ MPa, and a low modulus of elasticity (~ 70 ... 130 MPa) [14, 15]. Such fibers are non-combustible, can be used at temperatures up to 750 °C, have high adhesion to cement stone. The fire resistance of fiberglass concrete is higher than that of ordinary concrete. It depends on how well the fiber counteracts high temperatures and to what extent its bond with concrete is weakened during thermal expansion. fiberglass withstands temperatures of 600 ... 800 °C without undergoing changes. The use of fiberglass in order to increase the fire resistance of structures has not been studied enough. Similar results are shown by basalt fiber. The essence of the solution is to increase the tensile strength of concrete and increase crack resistance, due to which, under fire exposure, the integrity of the concrete protective layer is preserved for a longer time.

One of the methods for protecting concrete from explosive spalling in EN 1992-1-2 and a number of publications is the addition of 1-2 kg/m³ of polypropylene fiber (PPF) to concrete [16-18]. And we are talking not only about polypropylene structural fiber, but also about microfiber, the use of which is preferable. The fiber itself slightly increases the tensile strength of concrete. The functioning principle is that fiber takes up a certain volume in concrete, and when a fire is exposed to a structure, liquify and burn out, leaving pores in their place, through which water vapor freely enters the surface of the structure. Due to this, protection against explosive spalling is achieved. Therefore, it is extremely important to evenly distribute such fibers in concrete. Of course, the introduction of PPF significantly changes the technological properties of concrete mixtures and the physical and mechanical properties of concrete. In addition, it was experimentally determined that when PPF is added in a volume of 1
kg/m³, a decrease in the thermal conductivity is observed, which affects the increase in the time of heating of concrete and the decrease in the intensity of heating. Obviously, any synthetic fiber used in concrete can work according to this principle.

In construction practice, this method of protection against catastrophic failure of concrete has already been introduced in the construction of a 3.9 km long railway tunnel in Leipzig (Germany) [19]. In order to prevent catastrophic failure of reinforced concrete structures of tunnel structures, additives from polypropylene fibers in the amount of 2 kg/m³ were introduced into the concrete mixture.

4. Conclusions
As a result of the study, it was found that a very effective way to preserve the integrity of the reinforced concrete structure under fire exposure and, accordingly, increase its fire resistance is to modify the composition of concrete and control the structure in order to create a certain pore volume in concrete. However, the available data on the use of such methods are primarily empirical. There is a certain lack of theoretical base in terms of substantiating qualitative and quantitative indicators (type of fiber, length, diameter, mass and volume fraction of fiber in concrete, nature of porosity of cement stone, etc.). The possibility of combining mineral and synthetic fibers, as well as other methods to increase the fire resistance of concrete, has not been sufficiently studied. The issue is also complicated by the use of concrete of various classes, including high-strength, with lower porosity, higher thermal conductivity, and the behavior of such concrete at elevated temperatures differs from concrete of normal strength. Uncertainty is introduced by various possible modes of heating structures in a fire. It is necessary to study the theoretical foundations taking into account the existing accumulated experimental material, develop a universal methodology for the selection of compositions of such concrete, etc. These tasks seem relevant, in the future, having scientific and practical value.

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