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Estimation of fire resistance of bending reinforced concrete elements based on concrete with disperse fibers

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Abstract. The results of estimative calculations of bearing capacity, critical temperatures, and fire resistance ratings of reinforced concrete bending elements based on fiber concrete with disperse reinforcement of steel, basalt and synthetic fiber are presented. The calculations carried out on the example of a reinforced concrete rectangular beam both taking into account the percentage of reinforcement of each element and at a constant load corresponding to the condition of calculation adequacy showed that disperse reinforcement of a reinforced concrete bending element with steel, basalt and synthetic fiber increases its bearing capacity, but slightly affects critical temperature and fire resistance rating. Despite the fact that concrete with basalt fiber is the least sensitive to heat, concrete with steel and synthetic fibers turned out to be comparable in this indicator with ordinary concrete. The presented results of evaluative calculations allow predicting the use of bending reinforced concrete elements based on concrete with disperse fibers in conditions of increased fire hazard, depending on the percentage of reinforcement and on the workload.

1. Introduction

In modern construction, special attention is paid to reducing the weight of load-bearing building structures while maintaining their high strength. This approach is relevant for the construction of high-rise or large-span buildings.

To this end, at present, attempts are being made to increase the strength characteristics of concrete by introducing discrete fibers of various origins into its composition [1, 2]. As microfiber, fiberglass, steel, basalt or polymer fibers are used in such fiber-reinforced concrete. There is evidence that the strength of fiber-reinforced concrete can reach 30...35 MPa when bent, and when compressed, it can reach 80...100 MPa [3]. Studies have also shown that dispersed reinforcement of concrete increases their crack resistance, impact resistance, contributes to the resistance of concrete to aggressive environments; allows you to reduce the working section of the structures and in some cases to abandon the use of rod reinforcement or reduce its consumption [3, 4]. Therefore, despite the relative high cost, the use of fiber concrete is considered a promising direction. Improving the technology for the production of fiber concrete also contributes to their wider distribution through increased efficiency.

However, for all the listed advantages of products based on fiber-reinforced concrete, the problem of their stability in case of fire remains insufficiently investigated.

In [4], it was shown that with fiber reinforcement, self-healing of cracks in the stretched concrete zone is possible. This property determines the special mechanical characteristics of fiber concrete: an increase in ultimate elongation and fracture energy under compressive and tensile loads; increase in tensile and bending strength; increase in dynamic, fatigue and impact strength; low tendency to cracking with rapid changes in temperature. In the same work, the influence of the quantity, size and orientation of fibers on the mechanical and deformative characteristics of fiber concrete is considered. The determination of the parameters of building elements from fiber reinforced concrete is carried out according to the same principles as for reinforced concrete. The calculation in this case must be coordinated with the method of determining the internal forces and moments [5].

The existing experience in testing fire resistance of reinforced concrete structures indicates that, ceteris paribus, structures with higher mechanical characteristics usually have a greater fire resistance rating [6, 7, 8]. In the case of fiber reinforced concrete, due to the relatively short history of their use, the existing data on their fire resistance [9] do not allow to fully answer all the questions that arise. It can be assumed that the fiber material, changing the thermophysical properties of concrete, will affect the characteristics of its fire resistance [10, 11].

2. Statement of a problem and its decision

In this work, the fire resistance of reinforced concrete bending elements based on fiber concrete of different compositions was evaluated according to their calculated fire resistance ratings and critical temperatures of steel bar reinforcement.

For example, bending reinforced concrete elements with different percentages of reinforcement based on concrete of class C 20/25 with granite aggregate were selected as the base ones. The cross section of the elements is rectangular with dimensions: b = 300 mm, h = 700 mm, h_0 = 650 mm. The calculated concrete compressive strength is R_b = 14.5 MPa. For this element, a single reinforcement with three steel rods of A400 class with a compressive strength of R_s = 355 MPa is accepted. Concrete cover is 30 mm.

For comparison, we considered similar elements based on the same concrete, but with dispersed reinforcement of steel, basalt, and synthetic fiber [12].

For the selected bending initial element and the element with dispersed reinforcement, the bearing capacity relative to the center of gravity of the section of the compressed zone of concrete was calculated by the formula:

$$M = \sigma_s A_s (h_0 - 0.5x) , \tag{1}$$

where M is the bending moment; σ_s is the stress in the steel reinforcement; A_s is the total cross-sectional area of steel reinforcement; x is the estimated height of the compressed zone.

The equilibrium conditions for the calculations are selected:

– in the source element:

$$\sigma_s A_s - R_b bx = 0 , \tag{2}$$

– in elements with dispersed reinforcement:

$$\sigma_s A_s + R_f b(h - x)c_f \beta_f - R_b bx - R_f bxc_f \beta_f = 0 , \tag{3}$$

where R is the ultimate strength; indices s, b, f mean steel, concrete and fiber, respectively; b is the beam width; c_f is the volumetric concentration of fiber in concrete; β_f is the coefficient of volumetric adhesion of the fiber with concrete.

Condition (3) makes it possible to take into account the contribution of the fiber in counteracting tensile forces in the stretched concrete zone under the assumption that the coefficient of volumetric adhesion of the fiber to concrete in the compressed and stretched concrete zone is the same.

The estimated height of the compressed zone of concrete was calculated from the equilibrium condition as:

$$x = \xi \cdot h_0 , \quad (4)$$

where ξ is the relative height of the compressed zone of concrete.

Calculations of the bearing capacity of the bending elements were carried out according to the methodology [12] taking into account the material properties of the corresponding elements, and the results are shown in table 1.

Table 1. Calculated values of the bearing capacity and fire resistance rating of bending reinforced concrete elements with fiber reinforcement

Diameter of steel rods (mm)		22	28	36	40
Total cross-sectional area of steel reinforcement A_s (m^2)		0.00114	0.001847	0.003054	0.003768
Percentage of reinforcement (%)		0.5	1.0	1.5	2.0
Bearing capacity M (kN·m)	Initial element	152	312	476	605
	Steel fiber	219	395	542	676
	Basalt fiber	200	365	525	672
	Synthetic fiber	186	350	513	662
Critical temperature (ºC) / fire resistance rating τ (min) (for the bearing capacity corresponding to the percentage of reinforcement of each element)	Initial element	546/105	531/99	518/92	495/80
	Steel fiber	498/95	498/94	496/91	495/83
	Basalt fiber	520/100	512/98	500/95	482/90
	Synthetic fiber	540/103	531/100	502/93	470/85
Critical temperature (ºC) / fire resistance rating τ (min) (for constant load M = 340 kN·m)	Initial element	547/63	563/65	590/67	608/70
	Steel fiber	559/64	575/67	600/69	620/72
	Basalt fiber	557/63	574/66	599/68	619/71
	Synthetic fiber	555/63	574/66	598/67	617/71

The critical temperature of steel reinforcement of bending concrete elements was calculated according to the tables from the relation:

$$\gamma_{st} = \frac{M}{R_s A_s h_0 (1 - 0.5\xi)} , \quad (5)$$

where γ_{st} is the coefficient of decrease in bearing capacity during heating.

The fire resistance ratings of the studied reinforced concrete elements τ were estimated taking into account their bearing capacity according to the method [13] from the formula:

$$erf \frac{k\sqrt{a_b} + \delta}{2\sqrt{a_b \tau}} = erf X_b = \frac{t_l - t_{crS}}{t_l - t_0} , \quad (6)$$

where k is the density coefficient of concrete; a_b is the thermal diffusivity; δ is the depth of concrete over the reinforcement; t_l is the temperature of a standard fire, t_l = 1250 °C; t_0 is the initial temperature, t_0 = 20 °C; t_{crS} is the critical temperature of steel reinforcement.

The values of the characteristics of the materials used for the calculations are presented in table 2.

The critical temperatures of steel reinforcement and fire resistance ratings of the studied reinforced concrete elements were calculated both for the bearing capacity corresponding to the percentage of reinforcement of each element (option 1), and at a constant load of M = 340 kN·m, corresponding to the calculation adequacy condition (option 2).

The results of the estimated calculations of the critical temperature and fire resistance ratings of the bending elements are shown in table 1.

The graphs based on the calculation results are shown in Fig. 1.

Table 2. Characteristics of materials

	Young's modulus (MPa)	Breaking limit (MPa)	Coefficient of thermal conductivity ($W \cdot m^{-1} \cdot K^{-1}$)	Coefficient of heat capacity ($W \cdot h \cdot kg^{-1} \cdot K^{-1}$)
Steel A400	200000	355	–	–
Concrete C 20/25	30000	14.5	1.041	0.302
Concrete C 20/25 and steel fiber	150000	95	1.045	0.279
Concrete C 20/25 and basalt fiber	70000	60	1.041	0.302
Concrete C 20/25 and synthetic fiber	35000	35	1.037	0.325

Estimation calculations showed that, despite the increase in the mechanical properties of fiber-reinforced concrete with steel, basalt and synthetic fibers, the critical temperatures of bending reinforced concrete elements vary slightly compared to the initial element. The fire resistance rating also changes slightly.

This is clearly seen in the case of calculations under constant load (option 2). The fire resistance rating varies slightly in the range from R63 to R71. Moreover, this indicator does not depend on the composition of concrete.

In the case when the bearing capacity was selected taking into account the percentage of reinforcement corresponding to each element (option 1), the range of variation of the fire resistance rating was greater: for beams with steel and basalt fiber 10-12 min; for beams without fiber reinforcement and with synthetic fiber 20-25 min.

An experimental study of the behavior of reinforced concrete beams with a thickness of 700 mm and a concrete cover of 34 mm at high temperatures in [14] showed that they have an average fire resistance of R62. These experimental data correlate with our calculated values.

In an experimental study of the effect of high temperatures on concrete with steel [15] and polypropylene fiber [16], it was noted that with a temperature increase of more than a certain value (500 °C for steel fiber and 200 °C for polypropylene fiber), the positive mechanical effect disappears. From this it follows that the fire resistance ratings of beams made of these materials should not vary greatly between each other. This is exactly what our calculated data demonstrate.

The noted features are related to the fact that the critical temperature of steel reinforcement of reinforced concrete elements mainly depends on the magnitude of the load and the strength of steel reinforcement and weakly depends on the strength of concrete. And the fire resistance of reinforced concrete elements depends not only on the critical temperature of steel reinforcement, but also on the thermophysical characteristics, structure and thickness of the concrete cover.

Therefore, for option 1, in which the calculation of the critical temperature of steel reinforcement and fire resistance rating was carried out for the bearing capacity corresponding to the percentage of reinforcement of each element, these characteristics decreased with increasing percentage of reinforcement due to an increase in stress in the tension region of the element.

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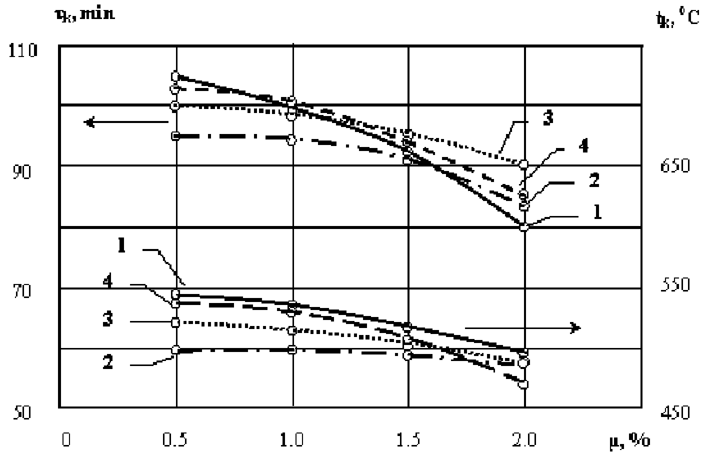
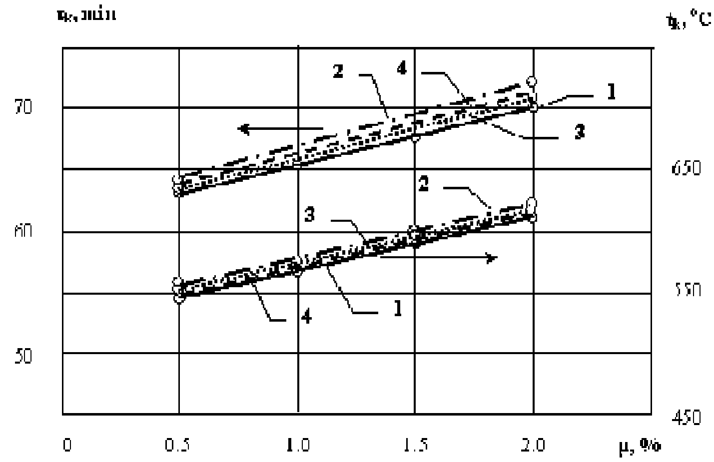


Option 1



Option 2

Figure 1. Dependences of the critical temperature and fire resistance of bending reinforced concrete elements with fiber reinforcement on the percentage of reinforcement of steel reinforcement when calculated according to option 1 and option 2: 1 – without fiber reinforcement; 2 – steel fiber; 3 – basalt fiber; 4 – synthetic fibers

For option 2, in which the calculation of the critical temperature of steel reinforcement and fire resistance rating was carried out under constant load, with an increase in the percentage of reinforcement, the stresses in the extended zone of the element decreased and, accordingly, the studied characteristics increased.

As expected, basalt fiber concrete is the least sensitive to heat. But concrete with steel and synthetic fibers turned out to be comparable in this indicator with ordinary concrete. Perhaps this is due to the fact that during the heating of steel reinforcement to a critical temperature, the calculated height of the compressed zone of fiber-reinforced concrete remains greater than that of ordinary concrete.

It should be noted that the calculations did not take into account the fact that synthetic fiber has low heat resistance. This may adversely affect the fire resistance of the element in which it is contained.

3. Conclusion

The fire resistance characteristics of reinforced concrete flexible elements based on fiber reinforced concrete with steel, basalt and synthetic fiber are estimated. This assessment was carried out according to the methodology [13] on the example of reinforced concrete beams with different percentages of reinforcement.

A comparison of the results with known experimental studies showed a satisfactory correlation.

Evaluation calculations showed that the dispersed reinforcement of a reinforced concrete bending element with steel, basalt and synthetic fibers increases its bearing capacity, but, ceteris paribus, slightly affects the critical temperature of steel reinforcement and the fire resistance of the element. It has been suggested that this effect is due to the fact that during the heating of steel reinforcement to a critical temperature, the calculated height of the compressed zone of fiber-reinforced concrete remains greater than that of ordinary concrete.

The presented results of evaluative calculations allow predicting the use of bending reinforced concrete elements based on concrete with disperse fibers in conditions of increased fire hazard, depending on the percentage of reinforcement and on the workload.

However, these estimated results do not negate the need to test structures made of fiber reinforced concrete for fire resistance, because the interaction of fiber and concrete material during heating is still not well understood.

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