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Strength and Fracture Toughness of Heat-Resistant Fiber-Reinforced Concrete

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Abstract. A technique is proposed for determining the critical length of a main crack in concretes at different loading rates. A composition of light, heat-resistant fiber-reinforced concrete of increased strength and crack resistance, which does not require heat treatment, has been developed. The effect of high temperatures on the change in the strength and fracture resistance of heat-resistant heavy and light concretes was studied.

1. Introduction

To control the development of cracks in concrete after influence of high temperatures or fire, it is necessary to determine the basic parameters of fracture mechanics not only at the initial and final moments of loading, but also during the slow growth of cracks. Currently, the establishment of accurate numerical values of these parameters is difficult, since the experimental data are limited or contradictory due to the use of different techniques.

2. Relevance

In concrete, characterized by a heterogeneous structure, the destruction is accompanied by the preliminary development of plastic deformations near stress concentrators. Disclosure and further uncontrolled growth occurs at the time of reaching a critical crack for each material. Among the few existing methods for determining the critical length of the main crack (macro crack) [1-9], a method is known [9], based on testing a batch of samples with an artificially created crack that is twice the maximum size of inclusions of a composite material and a batch of samples without such a crack. The critical crack length was determined by the values of stress limits. The disadvantage of the method [9] is the low accuracy and reliability of determining the critical length of the macro crack, due to the fact that strength limits of the test specimens with an artificial crack and without it were determined only at one (standard) loading rate. However, crack growth resistance (fracture toughness) depends on the loading rate.

3. Problem statement

When testing the composite material, in particular concrete, the value of the critical length of the macro crack, equal to the maximum size of the inclusions of concrete, and 10 times smaller than the linear dimension of the sample over which the crack developed was obtained in [9], cannot be considered reliable. Numerous studies using tensometric and other methods have established that the critical crack length can reach half the size and more of the cross section of a concrete sample. This is due to the inhibition of the crack when it hits stronger solid filler and pores. Further progress of macro



cracking occurred only with an increase in the current load, since the accumulation of additional energy was required.

4. Theoretical part

To improve the accuracy and reliability of determining the critical length of the main crack, a technique has been developed [10], which consists in the following. The bending force is loaded at various rates and the samples with an artificially created crack perpendicular to this force and identical samples without such a crack are brought to destruction. The values of the dynamic hardening coefficients obtained as a result of testing batches of samples at different loading rates determine the critical length of the main crack according to the formula [10]:

$$l_{cr} = h \cdot Y \cdot (K'_{dh} / K_{dh}) \quad (1)$$

where l_{cr} is the critical length of the main crack, m; h is the linear size of the sample (thickness or height) along which the crack develops, m; Y - function, depending on the shape of the sample and test scheme; K'_{dh} - coefficient of dynamic hardening of samples with an artificially created crack; K_{dh} - coefficient of dynamic hardening of samples that do not have an initial artificially created crack.

As is known, the coefficient of dynamic hardening shows the ratio of the tensile strength of the sample obtained at the maximum loading rate (i.e., at which the strength increase ceases) to the ultimate strength obtained at a minimum (below the standard) loading rate (i.e., where the strength is minimal). The use instead of the ultimate strength, determined only at one (standard) loading rate, the dynamic hardening coefficient makes it possible to more accurately determine the start time of the main crack (minimum strength at the lowest loading rate) and the instant the specimen reaches its ultimate mechanical state, i.e. destruction (maximum strength at maximum loading speed).

The greater the difference in strengths obtained on samples with an artificial crack and without it, or the smaller the ratio (K'_{dh} / K_{dh}), the higher the sensitivity of the material to the formation of cracks and the less its critical length. The larger the ratio (K'_{dh} / K_{dh}), the less material is sensitive to the formation of macro cracks and the greater its critical length.

The proposed method [10] is carried out as follows. Two sets of twin specimens are made from concrete, one of which is artificially cracked by inserting a special plate in the process of making a sample or by means of a cut with a special diamond-coated disc after the strength is set by the material. The size of the artificial crack is not less than 2 times the maximum size of the concrete inclusions, and the ratio of the crack length to the sample cross-section height a / h is 0.2-0.4. Sample dimensions exceed the maximum size of a large aggregate not less than 10 times. The test of two batches of samples is carried out by a tensile load over a wide range of loading rates. With increasing loading speed, the strength of concrete samples increases to a certain extent. A further increase in the loading rate does not lead to an increase in strength due to the absence of crack growth. From the strength values obtained, the dynamic hardening coefficients in each batch of samples are determined, and the critical length of the main crack is determined from them. The influence of an aggressive environment and high temperature leads to significant changes in strength, crack resistance and, ultimately, the service life of concretes used in the construction of heat engineering structures. In real-life operating conditions, under the influence of high temperature and load, concretes with the same strength can have different fracture toughness values, which must be taken into account when choosing the type and composition of concrete.

5. Results of experimental studies

Complex studies of the crack resistance of heat-resistant Portland cement concrete were carried out. The critical length of the main crack was determined by comparative tests using the known fracture mechanics technique - Interstate Standard (GOST 29167) and the proposed method. Samples-beams measuring 100×100×400 mm with an artificial notch 40 mm long and without it were made. The

samples were tested after heating at temperatures of 110, 300 and 800°C. Determination of the critical length of the developing main crack from the standpoint of fracture mechanics was carried out during equilibrium testing of samples using capillary and tensometric methods. Table 1 presents the comparative data of the critical length of the macro crack obtained by the methods of fracture mechanics l_{cr}^{st} and the proposed method l_{cr} [10].

Table 1. Influence of the heating temperature on the change in strength and crack resistance characteristics of heat-resistant concrete.

T, °C	R _{btf} , MPa ^a	R _b , MPa ^b	K _{IC} , MN / m ^{3/2} ^c	K _{dh}	K' _{dh}	l st _{cr} , m	l _{cr} , m
20	2.80	21.5	1.45	1.92	1.08	0.068	0.063
110	2.10	18.3	1.08	2.08	1.12	0.067	0.060
300	1.80	16.7	0.91	2.14	1.14	0.065	0.059
800	1.16	8.6	0.58	2.50	1.30	0.063	0.058

^a R_{btf} is the ultimate tensile strength.

^b R_b is the compressive strength.

^c K_{IC} is the critical stress intensity factor.

Analysis of the results showed that the obtained values of the critical length of the main crack l_{cr} , determined at different loading speeds of the samples, practically coincide with analogous values determined by the methods of fracture mechanics. A certain increase in (7-10) % of the length of the main crack, obtained in tests using a well-known standardized procedure, is due to the fact that the loading was carried out step-by-step with exposures (60-120) seconds. However, this discontinuity in the tests does not allow for constant monitoring of the growth of the macro crack in any time interval, which may introduce a certain error in the measurements, for example, the onset of uncontrolled crack growth until the end of the next stage of loading.

In order to increase the compressive strength and tensile strength in bending, as well as crack resistance, a light refractory fibro concrete composition [11, 12] was developed that does not require heat treatment. In comparison with the known concrete [13,14] used in heat engineering structures, the proposed composition, while maintaining high heat-resistant properties, has low density and high enough strength, especially for bending stretching. With the aim of recycling industrial waste to improve the environment safety in the development compositions, waste from various industries was used [15-18].

The porous structure of concrete created with the help of gas generators differs by sufficiently strong pore partitions formed as a result of the use of alumina slag and sulphate sludge interacting with orthophosphoric acid and aluminum powder. Sulfuric acid sludge is a product formed by the etching of scale in the manufacture of steel pipes with sulfuric acid followed by neutralization with limestone. The resulting waste in the form of sludge did not find application and in large quantities was exported to the dump, worsening the ecological state in the region.

The chemical composition of the slurry includes: Fe₂O₃ - (10-15)%; MgO - (3-5)%; SiO₂ - (7.0-7.3)%; CaSO₄ - (25-30)%; Cr₂O₃ - 1%; CaF₂ - (25-30)%, etc. The content of Si, Cr, Mg and Fe oxides in the sludge is a positive factor for use in refractory mixtures, since the H₃PO₄ phosphate systems containing these cations have high strength and heat-resistant properties.

Reduction in the density of the products obtained is due to hydrogen evolution and the use of expanded vermiculite sand fraction (0-5) mm, which differs significantly from claydite with a much lower density while maintaining high heat-resistant properties.

To increase the strength and crack resistance of concrete to tensile strength the use of various fiber grain as micro-reinforcing components, is effective [19-29]. Unlike the known light refractory concretes, the proposed raw material mixture for the production of light refractory fibro concrete,

including aluminum powder, 60% concentration of orthophosphoric acid, alumina slag, sulfuric acid sludge, vermiculite, additionally contains fiber grain from the wire "Chromel T" (relative length - 60).

The raw material mixture after solidification can be used in the construction of heat engineering structures, which, in addition to the compressors, experience considerable tensile stresses. The wire of the alloy HX 9.5 "Chromel T", used for the manufacture of thermocouples and containing 8-10% chromium and 90-92% nickel, is characterized by high tensile strength (up to 500 MPa) and high refractory properties.

Preservation of the given density of the obtained products in comparison with the known compositions [13, 14] is provided by the fact that the amount of vermiculite of the 0-5 mm fraction is increased in the proposed raw mixture, while the amount of alumina slag with an increased density is reduced.

Thus, the introduction of metal fiber grain made of wire HX 9.5 "Chromel T" into the raw material mixture, as well as an increase in the consumption of light vermiculite filler while reducing the amount of more dense alumina slag, provides a quick - hardening mixture of increased compressive and tensile strength while maintaining low density, high heat resistance and curing time.

To compare the physical and mechanical properties of the proposed lightweight heat-resistant fiber-reinforced concrete and known compositions of light refractory concrete [13], samples were prepared that were subjected to compressive and tensile strength, heat resistance, shrinkage, deformation under load, etc. tests.

Results are shown in Table 2.

Table 2. Physical and mechanical properties of the proposed compositions of light heat-resistant fibre concrete.

Properties of light refractory fiber-reinforced concrete	Known composition [13]	Compositions of raw mix		
		1	2	3
Curing time, min.	28-30	29	30	31
Compressive strength, MPa	2.2-3.2	3.91	4.15	4.53
Tensile strength, MPa	0.32-0.87	1.18	1.29	1.84
Average density, g / cm ³	0.53-0.64	0.58	0.62	0.64
Concrete class according to the maximum permissible application temperature	I 8 (T=800°C)	I 8	I 8	I 8
Residual strength after heating to 800°C, %	62-67	75	75	78
Thermal resistance at 800°C, air thermal changes	35-38	40	41	41
Temperature of 4% deformation under load, °C	800	1200	1200	1200
Limit value of shrinkage after heating up to the maximum permissible application temperature, %	1.8-2	1.8	1.7	1.62

Analysis of the data presented in Table 2 shows that the introduction into the raw mix of metal fiber grain from the "Chromel T" alloy having high refractory properties, with the specified ratios of the components included in it, contributes, according to the composition No. 3, to an increase in the compressive strength by 1.4 times, and tensile strength by 2.1 times while maintaining the average density of products and the same in comparison with the known composition [13] curing time.

The availability of data on the physical structure of light refractory fibre concrete, its resistance to the nucleation and growth of cracks under various environmental conditions allow us to proceed to a quantitative assessment of crack resistance. In the case of operating conditions, the tests were carried out in the heated state at temperatures of 110, 300 and 800°C.

As a result of the experiments, the equations and corresponding graphs of the strength and crack resistance dependence on the heating temperature were obtained. Analysis of the test results showed

that when the light fiber reinforced concrete was heated from 20°C to 800°C, the strength parameter R_{btf} decreased by 8%, while the fracture toughness index decreased by 15%. Such a slight decrease in the above parameters is associated with the structure of fiber-reinforced concrete. When heated to 800°C, the total porosity decreased by 3% with a slight redistribution of pore volumes by size.

The use of refractory aggregates from alumina slag and sulphate sludge, as well as metal fiber grain made of HX 9.5 "Chromel T" wire, helped stabilize the structure of fiber-reinforced concrete and the permanence of its mechanical characteristics.

In additional tests, the critical temperature (1500°C) of the proposed composition of light refractory concrete is established, at which the loss of strength is 70% of the initial value compared with the strength at 20°C.

6. Conclusions

The use of the developed compositions of light heat-resistant fiber-concrete will increase the strength, crack resistance and durability (service life) of heating engineering structures, as well as improve the environmental situation, reduce costs through the use of non-recycled waste aluminum and pipe industries and complete absence of heat treatment.

Thus, the proposed technique for determining the critical length of the main crack is consistent with the known method of fracture mechanics is highly accurate and reliable due to a comprehensive study of concrete samples under continuous tests with different loading rates.

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