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EFFECT OF MODIFIER MB10-01 ON THE PARAMETERS OF FRACTURE MECHANICS OF HIGH-STRENGTH COARSE-AGGREGATE CONCRETE

G. E. Okolnikova, M. Kharun*

Department of Architecture & Civil Engineering, RUDN University, Moscow, Russia

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ABSTRACT

The mass production of high-strength concretes (HSC) in Russia is mainly associated with the use of organomineral modifiers of the MB series, containing in their composition micro silica, fly ash, super plasticizer C-3 and hardening regulator in different ratios. In our study we produced HSC samples, with the compressive strength of at least 100 MPa, with dimensions of 100x100x100 mm – four series, 100x100x450 mm – four series, 100x100x450 mm with the artificial crack of 25 mm deep in the middle of the span – four series, and also 100x75x450 mm (75 mm height was taken equal to the height of the section above the crack of the 2nd type of prisms) – four series. The actual HSC grade on compression, the tensile strength at bending, the strength at axial tension, the elasticity modulus, the cracking moment, and also the parameters of fracture mechanics, such as: the critical stress intensity factor and the critical energy release rate, at the curing periods of 7, 14, 28, 60 days, have been determined. We also evaluated the influence of crack in the bend element on the value of the cracking moment. The research results have been implemented in the construction of high-rise buildings of the Moscow International Business Center "Moscow City", and in the reconstruction of the Engineering Faculty building of the RUDN University.

Keywords: Cracking moment, Critical energy release rate, Critical stress intensity factor, Tensile strength at bending, Strength at axial tension

Author Correspondence, e-mail: miharun@yandex.ru

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INTRODUCTION

Currently, constructions of high-rise buildings are being intensively carried out all over the world. Every year construction projects are becoming more and more challenging.Infrastructure development requires high-performance materialswhich provide not only the possibility of erecting the objects, and also allow the use of optimal architectural and structural solutions.

Over the past decades, research has been carried out on the basic physical and mechanical properties of high-strength concretes (Bastami M. et al., 2014;Elchalakani M., 2015;Grabiec A.M. et al., 2015;Hasan H.A. et al., 2017; Karpenko N.I. et al., 2015; Long G. et al., 2017), but the parameters of fracture mechanics parameters were not sufficiently studied.

The classical fracture mechanics applied to conditionally homogeneous materials originates from Griffiths A., later developed by Bolotin V.V., Irvin J., Morozov E.M., LeonovM.Ya., Parton V.Z., and others (Okolnikova et al., 2016; Usov B.A. and Okolnikova G.E., 2016). For concrete, which is substantially an inhomogeneous material, the applicability of the methods of classical fracture mechanics is not advisable (Karpenko N.I. et al., 2010;Karpenko N.I. et al., 2015; Negrutiu C. et al., 2016).Failure of high-strength and ultra-high-strength concrete has its own features associated with the characteristics of crack resistance of individual components of the concrete structure, such as: filler, matrix, contact area between the filler and the matrix (Negrutiu C. et al., 2016;Ranade R. et al., 2015;Sharmila P. and Dhinakaran G., 2016).

The mass production of HSC in Russia is mainly associated with the use of organomineral modifiers of the MB series, containing in their composition microsilica, fly ash, superplasticizer C-3 and hardening regulator in different ratios (Usov B.A. and Okolnikova G.E., 2015). Many researchers studied the physical and mechanical properties of HSC prepared with MB modifiers (Karpenko N.I. et al., 2015;Karpenko N.I. et al., 2010;Usov B.A. and Okolnikova G.E., 2016; Okolnikova G.E. et al., 2017), but the parameters of fracture mechanics remained unexplored.

The aim of the study is to determine the parameters of fracture mechanics, such as the critical stress intensity factor and the critical energy release rate, and also to evaluate the influence of crack in the bend element on the value of the cracking moment,of HSC prepared with theMB modifier.

MATERIALS AND METHODS OF RESEARCH

Within this study we selected as the basic research materialHSC, prepared with the modifier MB10-01(an admixture on anorganomineral basis containing micro-silica, fly ash, super plasticizer C-3 and hardening regulator), with the compressive strength of at least 100 MPa, which finds an increasing application in the contemporary construction.

The study of HSC was carried out with the following composition: Portland cement of type I = 490 kg/m^3; concrete modifier MB10-01= 110 kg/m^3; sand with the fineness modulus of 2.7 = 880 kg/m^3; crushed granite with the fraction of 5-15 mm = 730 kg/m^3; water = 140 l/m^3.

Laboratory experiment was carried out in accordance with the CIS Interstate Standard"GOST"(GOST 10180-2012, 2013;GOST 53231-2008, 2009).

Within this study we produced total sixteen series of test samples of HSC from the stated composition with dimensions of 100x100x100 mm – four series; 100x100x450 mm – four series, 100x100x450 mm with an artificial crack of 25 mmdeep in the middle of the span – four series, and also 100x75x450 mm(75 mm height was taken equal to the height of the section above the crack of the 2nd type of prisms) – four series.

The dimensions of the cross-sections of the prisms were chosen in such a way that the results of the laboratory test could determine the parameters of fracture mechanics, and also assess the influence of the stress concentrator in the form of crack in the tensile zone at the cracking moment. Therefore, the height of the cross-section of the third type of prisms was taken equal to the cross-sectional height above the artificial crackin the middle of the span of the second type of prisms – 75 mm.

In accordance with the plan of experiment, each series consists of three samples, twelve in every type, total 48 samples.All samples were cured in air-humid condition in wet sawdust at the room temperature of 19-22 °C.

Laboratory tests were carried out at the curing periods of 7, 14, 28, 60 days on a hydraulic press of up to 5000 kNat the compression test, and up to 200 kN at the bending test.

Compressive strength was identified by the following formula(GOST 10180-2012, 2013):

$$R_c = \alpha \cdot \frac{F_c}{A}$$

where α – the scale factor on compression test, α = 0.95 for cubes of the dimensions of 100x100x100 mm; F_c – the failure load on compression; A – the surface area of the sample.

The concrete grade was identified by the formula(GOST 53231-2008, 2009):

$$C_f = 0.8\ R_t$$

where R_t – the actual concrete strength according to the test data, $R_t = R_c \cdot \alpha$.

Tensile strength at bending was identified by the following formula(GOST 10180-2012, 2013):

$$R_{ct} = \delta \cdot \frac{F_t \cdot l}{a \cdot b^2}$$

where δ – the scale factor for tensile test, δ = 0.92 for prisms of the dimensions of 100x100x450 mm; F_t – the failure load on tensile; l – the distance between supports during sample testing; a, b – the width and the height of the cross section of the sample accordingly.

Strength at axial tension was identified by the formula(Regulation Code 63.13330.2012, 2015):

$$R_{ctf} = \frac{R_{ct}}{1.75}$$

Cracking moment was identified by the following formula(Regulation Code 63.13330.2012, 2015):

$$M_{crc} = R_{ct} \cdot \frac{bh^2}{3.5}$$

where b, h – the width and the height of the cross section of the sample accordingly.

Critical stress intensity factorwas identified by the formula (GOST 10180-2012, 2013):

$$K_{Ic} = \sigma_{nc} \sqrt{(\pi \cdot l)} \cdot Y(\lambda)$$

where σ_{nc} – the nominal normal stress; π = 3.1416; l – the length of artificial crack; $Y(\lambda)$ – the correction polynomial,

$$Y(\lambda) = \frac{(1-\lambda)^2}{\sqrt{\pi}} \left[2 - 2.5\lambda + 13\lambda^2 - 23.2\lambda^3 + 24.8\lambda^4\right]$$

here $\lambda = l/h$, l – the length of artificial crack; h – the height of the cross section of the sample.

Critical energy release rate was identified by the following formula (GOST 10180-2012, 2013):

$$G_{Ic} = \frac{(K_{Ic})^2}{E}$$

where E – modulus of elasticity.

RESULTS AND DISCUSSION

The most important physical and mechanical properties of concrete are the compressive strength, tensile strength at bending, strength at axial tension, cracking moment and concrete grade.

In addition, in order to assess the load-bearing capacity of the reinforced concrete structure from the position of fracture mechanics, the characteristics of the crack resistance of concrete are important, particularly: the critical stress intensity factor and the critical energy release rate.

In the framework of this study we carried out the experimental determination of the compressive strength, the tensile strength at bending, the strength at axial tension, the cracking moment and the concrete grade at axial compression, as well as the characteristics of the crack resistance: the critical stress intensity factor and the critical energy release rate of HSC prepared with modifier MB10-01. The following types of test samples were examined:

1. Four series of samples of 100x100x100 mm of cube shape were tested to determine the compressive behavior(Table 1).

2. Four series samples of 100x100x450 mm of prism shape were tested to determine the tensile behavior (Table 2).

3. Four series samples of 100x100x450 mm of prism shape with artificial crack of 25 mm deep in the middle of the span were tested to determine the tensile behavior, as well as parameters of fracture mechanics (Table 3).

4. Four series of samples of 100x75x450 mm of prism shape were tested to determine the tensile behavior for comparison with samples with artificial crack(Table 4).

Figure 1 shows the diagram of changes in compressive strength (cubic strength) of HSC depending on the curing period

Table 1. Result of the laboratory tests of HSC samples of 100x100x100 mm on the compressive behavior

Curing Period,Days	Sample Number	F_c,kN	R_c, MPa	α	R_t, MPa	AverageR_t, MPa	Actual HSC Grade
7	C1	781	78.1	0.95	74.2	71.53	C57
	C2	784	78.4	0.95	74.5		
	C3	694	69.4	0.95	65.9		
14	C4	900	90.0	0.95	85.5	89.13	C71
	C5	941	94.1	0.95	89.4		
	C6	974	97.4	0.95	92.5		
28	C7	1098	109.8	0.95	104.3	103.33	C82
	C8	1084	108.4	0.95	103.0		
	C9	1081	108.1	0.95	102.7		
60	C10	1153	115.3	0.95	109.5	105.66	C84
	C11	1071	107.1	0.95	101.7		
	C12	1114	111.4	0.95	105.8		

Table 2. Results of the laboratory tests of HSC samples of 100x100x450 mm on the tensile behavior

Curing Period, Days	Sample Number	F_t,kN	R_{ct}, MPa	R_{ctf},MPa	M_{crc},N.m	Average R_{ct}, MPa	AverageR_{ctf},MPa	Average M_{crc},N.m
7	P1	22.6	6.78	3.87	1105.7	6.87	3.92	1121.9
	P2	21.5	6.45	3.69	1054.3			
	P3	24.6	7.38	4.22	1205.7			
14	P4	25.5	7.65	4.37	1248.6	7.54	4.31	1231.43
	P5	24.6	7.38	4.22	1205.7			
	P6	25.3	7.59	4.34	1240.0			
28	P7	27.0	8.1	4.63	1322.9	7.73	4.41	1261.93
	P8	26.3	7.9	4.51	1288.6			
	P9	23.9	7.2	4.11	1174.3			
60	P10	28.0	8.4	4.80	1371.4	8.33	4.76	1360
	P11	28.8	8.6	4.91	1402.9			
	P12	26.8	8.0	4.57	1305.7			

Table 3. Results of the laboratory tests on the tensile behavior of HSC samples of 100x100x450 mm with artificial crack of 25 mm deep in the middle of the span

Curing Period, Days	Sample Number	F_t, kN	R_{ct}, MPa	R_{ctf}, MPa	M_{crc}, N.m	Average R_{ct}, MPa	Average R_{ctf}, MPa	Average M_{crc}, N.m	Average K_{Ic}, MPa·m$^{0.5}$	Average G_{Ic}, N/m
7	G1	11.32	6.04	3.45	554.5	6.01	3.44	554.4	0.612	9.82
	G2	11.28	5.86	3.35	552.8					
	G3	12.19	6.13	3.51	555.8					
14	G4	12.59	6.51	3.63	616.3	6.49	3.61	612.0	0.646	10.48
	G5	12.54	6.50	3.62	613.9					
	G6	12.35	6.48	3.58	605.8					
28	G7	12.87	6.59	3.77	658.4	6.64	3.80	660.1	0.662	10.62
	G8	13.30	6.78	3.87	664.1					
	G9	12.64	6.54	3.75	657.8					
60	G10	13.33	6.98	3.99	668.5	7.04	4.02	673.0	0.670	10.79
	G11	13.57	7.09	4.05	675.9					
	G12	13.85	7.05	4.03	674.5					

Table 4. Results of the laboratory tests on the tensile behavior of HSC samples of 100x75x450 mm

Curing Period, Days	Sample Number	F_t, kN	R_{ct}, MPa	R_{ctf}, MPa	M_{crc}, N.m	Average R_{ct}, MPa	Average R_{ctf}, MPa	Average M_{crc}, N.m
7	F1	12.27	6.72	3.84	600.8	6.61	3.77	590.37
	F2	11.83	6.48	3.70	578.9			
	F3	12.08	6.62	3.78	591.4			
14	F4	12.59	6.90	3.94	616.4	6.87	3.93	620.03
	F5	13.11	7.00	4.00	642.9			
	F6	12.27	6.72	3.84	600.8			
28	F7	13.92	7.33	4.26	682.2	7.21	4.15	667.23
	F8	13.79	7.26	4.19	675.0			
	F9	13.17	7.02	4.01	644.5			
60	F10	14.29	7.83	4.47	703.4	7.55	4.31	699.07
	F11	14.31	7.43	4.25	697.4			
	F12	14.23	7.39	4.22	696.4			

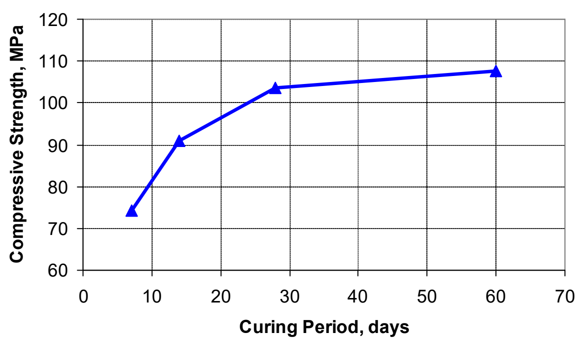

Fig.1. Compressive strength (cubic strength) of HSC depending on the curing period of HSC samples of 100x100x100 mm

Analysis of the diagram (Fig. 1) shows that the strength growth in HSC samples is smooth and uniform as in conventional concrete.

Study of our HSC samples(Table 1 and Fig. 1) prepared with modifier MB10-01 showed that the compressive strength in 7 days of curing can reach up to 66-74MPa,which is about 70% of the compressive strength of28 days curing period. It gives the possibility to load structures, such as HSC columns and walls, at an early age.

Diagrams of Fig. 2 and 3 show the kinetics of the tensile strength of HSC samples prepared with the modifier MB10-01 in bending and axial tension tests for three types prisms.

Analyzing the Tables 2, 3, 4 and the diagrams in Fig. 2 and 3, it can be concluded that the stress concentrator in the form of artificial crack reduce the tensile strength by an average of 14%, and a decrease in the cross-sectional height reduce the tensile strength by about 6%.Prisms of 100x100x450 mm with artificial crack and prisms of 100x75x450 mm have the same cross sectional height in the middle of the span, however, due to the presence of artificial crack, the tensile strength at bending (Fig. 2), and the strength ataxial tension (Fig. 3) decrease by an average of 8 %.

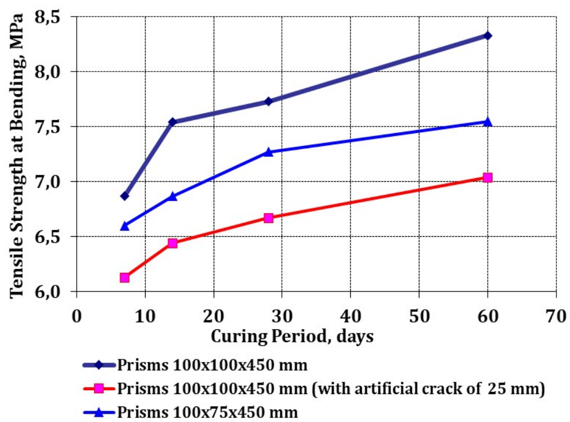

Fig.2. Dependency of the tensile strength at bending on the curing period of HSC samples

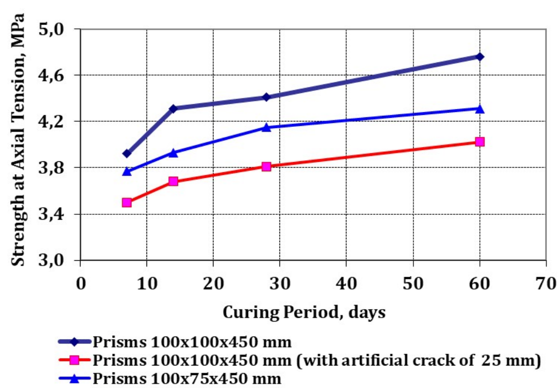

Fig.3. Dependency of the strength at axial tension on the curing period of HSC samples

After studying the three types of HSC prisms, prepared with the modifier MB10-01, it can be stated that the tensile strength of concrete was distributed as follows:the greatest strength is possessed by prisms of 100x100x450 mm without any artificial crack;the strength of prisms of 100x75x450 mm without artificial crack is reduced by an average of 6% due to a decrease in the cross-sectional height by 25 mm; the strength of prisms of 100x100x450 mm with an artificial crack in the middle of the span is reduced by an average of 14% due to the presence of the stress concentrator in the form of an artificial crack of 25 mm deep.

Fig. 4 shows the dependency of the cracking moment on the curing period of HSC samples of the prisms.

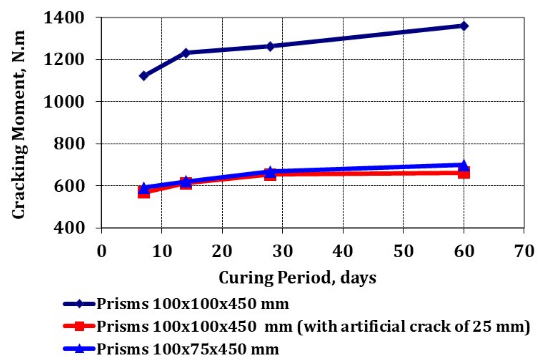

Fig.4. Dependency of the cracking moment on the curing period of HSC samples

In our research work, we planned to examine the two factors, the reduction of height of the cross-section of the bending element and the presence of an artificial crack in the tensile zone, to what extent these two factors affect the decrease in the cracking moment.

Analyzing the tables 2, 3, 4 and the diagrams in Fig. 4, the following conclusions can be drawn: a decrease in the cross-sectional height by 0.25 reduces the cracking moment by an average of 48%;the presence of a stress concentrator in the form of an artificial crack with the depth of 0.25 of the cross-sectional height in the tensile zone reduces the cracking moment by an average of 50%.

Fig. 5 and 6 show the dependency of the critical stress intensity factor and the critical energy release rate on the curing period.

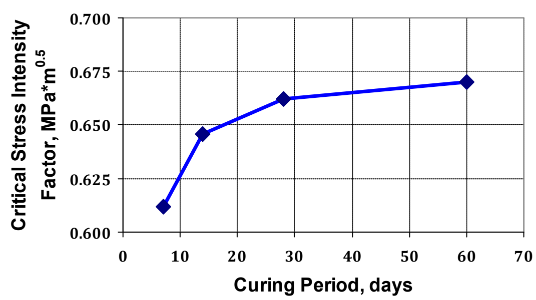

Fig.5. Dependency of the critical stress intensity factor on the curing period of HSC samples of 100x100x450 mm

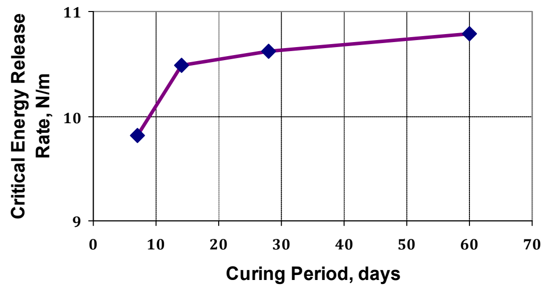

Fig.6. Dependency of the critical energy release rate on the curing period of HSC samples of 100x100x450 mm

Analysis of the Fig. 5 and Fig. 6 show that the critical stress intensity factor in HSC samples is smooth and uniform as in conventional concrete, however, the critical energy release rate increases intensely until 14 days.

The research results have been implemented in the construction of the Moscow International Business Center "Moscow City".

CONCLUSIONS

On the basis of the experimental study of HSC with the modifier MB10-01, the following parameters were identified:

1. The physical and mechanical properties, such as the compressive strength, the tensile strength at bending, the strength at axial tension, and the cracking moment.
2. The parameters of fracture mechanics, such as the critical stress intensity factor and the critical energy release rate, and also recorded their dependency on the curing period.
3. The influence of crack in the bend element on the value of the cracking moment.

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