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Influence of different sizes of concrete and roller compacted concrete on double-K fracture parameters

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ABSTRACT. Affected by physical properties of various components, characteristics and stress states of junction surface and other multiple factors, concrete, as a kind of multi-phase composite material, has complicated failure mechanism, thus making its fracture mechanism research difficult. But concrete has been widely used in engineering construction, so research on concrete fracture theory is of important realistic significance and construction value. This study discusses influence rule of specimen size and crack-depth ratio (α_0/h) on double-K fracture parameters (initial fracture toughness K_{IC}^{ini} and unstable fracture toughness K_{IC}^{un}) and its size effects by using fracture test. Different sizes of concretes and roller compacted concrete (RCC) specimens are adopted to explore influence of specimen size on concrete double-K fracture parameters. Results reveal that initial fracture toughness K_{IC}^{ini} and unstable fracture toughness K_{IC}^{un} increase as specimen size enlarges, showing a size effect; besides, subcritical crack extends with the increase of specimen size. With regard to specimens with different crack-depth ratios, its unstable fracture toughness K_{IC}^{un} is unrelated to initial crack-depth ratio when crack-depth ratio is more than or equal to 0.4, while initial fracture toughness K_{IC}^{ini} is correlated with initial crack-depth ratio, which indicate that double-K fracture parameters can be considered as material constants describing concrete initial fracture, stable expansion and whole process of stability failure.

KEYWORDS. Concrete; Fracture; Double-K fracture parameters; Crack-depth ratio.

INTRODUCTION

To date, fracture mechanics is applied in concrete structure from three aspects [1]: first is research on fracture mechanism of concrete; second is decision of endanger degree of some serious cracks in concrete structure, for example, stability analysis of crack in pier, upstream face crack in massive-head dam and pressure vessel crack of prestressed concrete (PC) in atomic power station; third is improvement of design method of concrete structure, for instance, decision of stability of various thorough cracks in concrete pouring blocks and calculation of cracking load of reinforced concrete (RC) in diagonal direction, etc. People are expected to improve design methods of gravity dam and arch dam using fracture mechanics [2].

Two-parameter model considers actual crack in combination with micro-crack zone as an effective crack, then obtains results using theory of linear elastic fracture mechanics and combines it with numerical computation method. Its essence lies in using valid crack tip opening displacement (CTOD) to reach critical valid CTOD, i.e., fracture criterion. Xu Shilang [3], a scholar from China, put forward a simple and applicable fracture criterion in 1999, namely, double-K fracture criterion. This criterion, belonging to the first type, not only corrects linear elastic fracture mechanics model based on a complete theory, but also decides its fracture parameters with the help of simple test methods, which is expected to be popularized and applied in practical engineering. Two fracture parameters are introduced into this criterion, initial fracture toughness K_{IC}^{ini} and unstable fracture toughness K_{IC}^{un}. Test indicates that those two parameters without size effect under a certain size, as fracture parameters, can be well applied in the analysis of concrete structure crack extension, and have drawn much attention [4-7]. A relevant trial [8] reveals that maximum seam strain is 10 times of average value of ordinary bending ultimate strain, which is exactly a ratio of theoretical strength and breaking stress of a point of concrete material. This thesis aims to explore characteristics of double-K fracture parameters (initial fracture toughness K_{IC}^{ini} and unstable fracture toughness K_{IC}^{un}) of concrete using data obtained from test.

DESIGN OF CONCRETE FRACTURE STIFFNESS TEST WITH WEDGE SPLITTING METHOD

Material Selection and Mix Proportion

Materials include tap water for life, 32.5 ordinary Portland cement, fly ash (level II), natural medium sand with particle size of over 5mm, macadam with maximum particle size of 20 mm (level I), high efficiency slushing agent suitable for mass concrete, and mix proportion is shown in Tab. 1. Wedge splitting specimen [14, 15] is adopted in this test (Fig. 1) and Tab. 2 displays specimen parameters. All specimens are divided into two categories containing 12 kinds of working conditions, the quantity of specimen in each working condition is presented in Tab. 2 and testing devices are in Fig. 2.

Materials	Tap water	Cement	Fly ash	Sand	Stones	Additives
RCC kg/m^3	130	134	90	805	1280	0.75%
Common concrete kg/m^3	203.7	407	0	535	1245	0

Table 1: Mix proportion of roller compacted concrete (RCC) and common concrete.

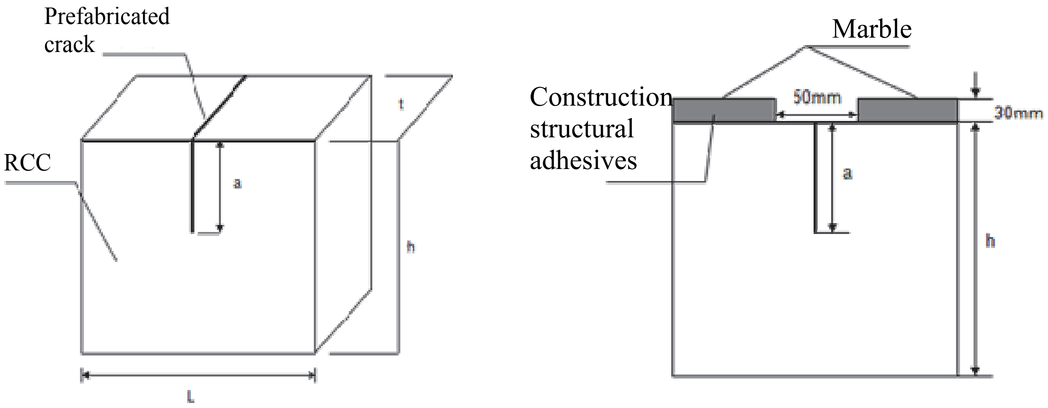

Figure 1: Shape and size of specimen.

Categories	Serial number	Quantity	Size of specimen (1×h×t/mm)	Crack-depth ratio	Depth of cracks [mm]	Thickness of cracks [mm]
RCC	RCC1504	12	150×150×150	0.4	60	3
	RCC1504	6	150×150×150	0.5	75	3
	RCC1504	6	150×150×150	0.6	90	3
	RCC1504	6	300×300×150	0.4	120	3
	RCC1504	6	400×400×150	0.4	160	3
	RCC1504	6	500×500×150	0.4	200	3
Common concrete	PC1504	9	150×150×150	0.4	60	3
	PC1504	6	150×150×150	0.5	75	3
	PC1504	6	150×150×150	0.6	90	3
	PC1504	9	300×300×150	0.4	120	3
	PC1504	9	400×400×150	0.4	160	3
	PC1504	9	500×500×150	0.4	200	3

Table 2: Working conditions of specimen.

Testing Devices

Testing devices are shown in Fig. 2.

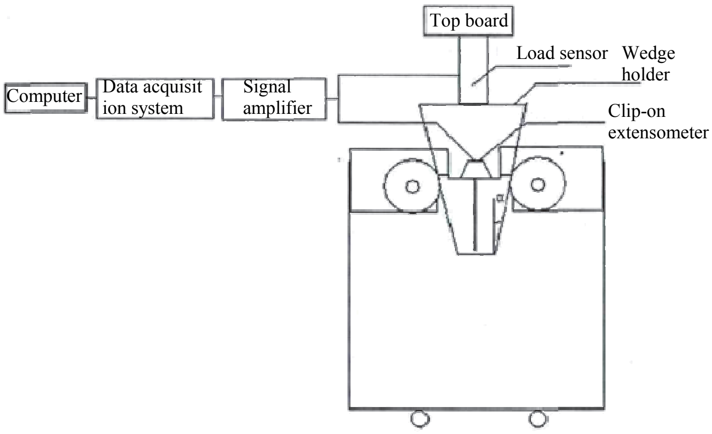

Figure 2: Acquisition of test data with wedge splitting method

Test Results

Specimen over 150×150×150 mm^3 is calculated with following formula, and specimen (150×150×150 mm^3) uses regular computing method [9-11]. Unilateral opening specimen is affected by axial tension, and stress intensity factor (SIF) can be calculated with formula below:

$$K_L^1 = \sigma\sqrt{\pi a f}\left(a / D\right) \tag{1}$$

where, $\sigma = P_b / \left(D \times t\right)$ and $f\left(a / D\right) = 1.122 - 0.231\left(a / D\right) + 10.55\left(a / D\right)^2 - 21.71\left(a / D\right)^3 + 30.382\left(a / D\right)^4$

Unilateral opening specimen is affected by bending moments only, and SIF is:

$$K_L^2 = \frac{6M}{tD^2}\sqrt{\pi a}\, g\left(a/D\right) \tag{2}$$

where, $M = 1/2P_h D - 1/2P_v e$ and $g\left(a/D\right) = 1.122 - 1.4\left(a/D\right) + 7.33\left(a/D\right)^2 - 13.08\left(a/D\right)^3 + 14\left(a/D\right)^4$

Overlapping formula (1) and (2), SIF expression of crack tip in any load time with wedge splitting geometry is obtained:

$$K_I = K_L^1 + K_L^2 \tag{3}$$

As some problems may exist in part of specimen making and maintenance, here, the quantity of several effective specimens with good surface, basically complete trial curve, small deviation and calculative in double-K fracture parameter is listed in Tab. 3.

Arithmetic mean value of initial fracture of 4~6 specimens from each group is taken as trial results. When the difference between single value and average value is over 15% of the average value, this value is excluded, and mean value of the rest of values is considered as trial result.

Trial result is:

$$\bar{K}_{IC} = \sum_{j=1}^{n} K_{ICj}\left(MPa\sqrt{m}\right) \tag{4}$$

Categories	Size [mm]	P [kN]	CMOD [mm]	E [GPa]	a_c [mm]	Δa_c [mm]	K_1	K_2	K_I
PC	300	4.91	141.1	19.45	166.4	46.5	0.432	0.872	1.304
PC	300	5.08	170.3	16.04	165.4	45.3	0.438	0.881	1.319
PC	300	4.61	130.4	18.02	160.5	40.4	0.381	0.771	1.152
PC	300	5.03	133.3	15.77	161.4	41.3	0.416	0.840	1.256
PC	300	4.52	118.0	21.36	165.5	45.3	0.399	0.804	1.203
PC	300	5.03	138.3	17.58	158.4	38.5	0.400	0.810	1.210
PC	400	5.55	183.9	16.53	234.4	74.5	0.466	0.913	1.379
PC	400	5.76	222.1	15.45	240.3	80.2	0.509	0.991	1.500
PC	400	6.60	245.5	16.02	241.6	81.6	0.582	1.131	1.713
PC	400	6.49	252.4	16.89	240.7	80.8	0.569	1.104	1.673
PC	400	6.44	266.9	15.32	245.2	85.3	0.592	1.145	1.737
PC	500	8.16	180.2	16.33	275.4	75.5	0.510	0.997	1.507
PC	500	8.31	210.2	15.78	298.5	98.4	0.615	1.183	1.798
PC	500	7.68	252.4	15.58	300.4	100.7	0.534	1.124	1.658
PC	500	8.26	208.6	20.00	300.1	100.4	0.621	1.193	1.814
RCC	300	4.53	155.0	15.51	174.0	54.2	0.444	0.887	1.331
RCC	300	5.37	226.3	14.91	176.2	56.0	0.525	0.903	1.428
RCC	400	5.58	221.1	16.19	245.0	85.3	0.521	1.010	1.531
RCC	400	5.76	216.3	14.38	248.1	88.1	0.554	1.070	1.624
RCC	400	4.78	200.7	15.33	243.0	83.0	0.457	0.890	1.347
RCC	500	8.30	239.8	15.02	314.2	114.2	0.705	1.039	1.744
RCC	500	6.92	246.4	15.00	309.8	109.9	0.604	1.154	1.758
RCC	500	6.37	257.5	15.09	311.9	112.0	0.546	1.043	1.589

Table 3: Trial results of various working conditions.

INFLUENCE OF CRACK-DEPTH RATIO ON CONCRETE FRACTURE STIFFNESS

Wedge splitting specimens (crack-depth ratio: 0.3:0.4:0.5:0. 6 and size: 150 mm × 150 mm × 150 mm) are selected for studying influence of a/h on double-K fracture parameter and crack mouth opening displacement (CMODc) and influence rule of crack-depth ratio in concrete fracture process and fracture strength.

Test Design

Tap water, 32.5 ordinary Portland cement, fly ash (level II), natural medium sand with particle size of over 5mm, macadam with maximum particle size of 20 mm (level I) and high efficiency slushing agent suitable for mass concrete are used in the test and their mix proportions are shown in Tab. 4.

Material	Tap water	Cement	Fly ash	Sand	Stones	Additives
RCC [kg/m^3]	130	134	90	805	1280	0.75%
Ordinary concrete [kg/m^3]	203.5	407.5	0	535	1245	0

Table 4: Mix proportions of RCC and ordinary concrete.

Wedge splitting specimen is applied in the trial, containing two categories (12 kinds of working conditions), and quantity of specimen in each working condition is shown in Tab. 5.

Categories	Serial number	Quantity	Size 1×h×t [mm^3]	Crack-depth ratio	Depth of cracks [mm]	Thickness of cracks [mm]
RCC	RCC1504	6	150×150×150	0.4	60	3
	RCC1505	4	150×150×150	0.5	75	3
	RCC1506	4	150×150×150	0.6	90	3
Ordinary concrete	PC1504	6	150×150×150	0.4	60	3
	PC1505	2	150×150×150	0.5	75	3
	PC1506	3	150×150×150	0.6	90	3

Table 5: Working conditions of specimen.

Phenomenological Analysis of Wedge Splitting Test

This test is carried out on a 200kN compression-testing machine and adopts formula to calculate valid crack growth quantity. From cracks in damaged trial (Figs. 3, 4), effective subcritical growth quantity can be obviously found in figures, and direction of crack growth is not smooth, which is mainly caused by reasons of concrete itself, as well as various construction aggregates. Cracks will bypass and keep on growing when encountering construction aggregates with large particle size.

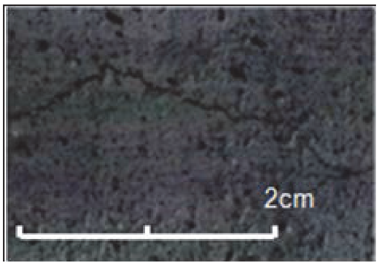

Figure 3: Damaged cracks of RCC specimen.

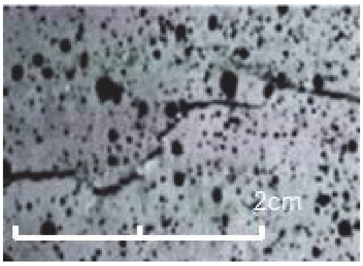

Figure 4: Damaged cracks of concrete specimen (type 150).

Analysis of Calculation Results

P-MOD curve character parameters of wedge splitting specimen are figured out based on test results (Tab. 6).

Serial number of specimen	Size (mm)	Crack-depth ratio	P_{max} [kN]	CMODc [mm]
RCC-1	150	0.4	5.29	110
RCC-2	150	0.4	5.08	115
RCC-3	150	0.4	6.13	89
RCC-4	150	0.4	4.52	109
RCC-5	150	0.4	4.70	109
RCC-6	150	0.4	5.13	102
RCC-7	150	0.5	4.62	163
RCC-8	150	0.5	4.69	139
RCC-9	150	0.5	4.65	152
RCC-10	150	0.5	4.23	155
RCC-11	150	0.6	3.03	215
RCC-12	150	0.6	3.61	186
RCC-13	150	0.6	3.97	189
RCC-14	150	0.6	4.02	229
C-1	150	0.4	7.76	101
C-2	150	0.4	6.70	92
C-3	150	0.4	7.71	98
C-4	150	0.4	5.44	101
C-5	150	0.4	5.53	96
C-6	150	0.4	5.75	93
C-7	150	0.5	6.19	102
C-8	150	0.5	6.20	103
C-9	150	0.6	6.52	101
C-10	150	0.6	6.31	100
C-11	150	0.6	5.98	113

Table 6: Basic test results.

Tab. 7 makes a list of unstable fracture toughness calculated by initial crack-depth ratio and maximum load P_{max},

Serial number of specimen	Valid crack growth quantity [cm]	Unstable fracture toughness [MPa√m]	Initial fracture toughness [MPa√m]
RCC-1	8.1	0.944	0.415
RCC-2	8.6	1.039	0.316
RCC-3	8.3	1.016	0.420
RCC-4	7.8	0.968	0.351
RCC-5	8.7	0.957	0.344
RCC-6	7.8	0.996	0.486
RCC-7	9.9	0.775	0.385
RCC-8	9.4	0.784	0.360
RCC-9	9.6	0.811	0.407
RCC-10	9.5	0.797	0.359
RCC-11	11.6	0.815	0.361
RCC-12	11.4	0.900	0.307
RCC-13	10.9	0.852	0.305
RCC-14	11.6	0.948	0.269
C-1	8.3	1.01	0.481
C-2	7.7	1.06	0.582
C-3	6.8	1.09	0.555
C-4	8.0	1.05	0.648
C-5	7.9	1.11	0.621
C-6	7.8	1.19	0.648
C-7	8.7	1.18	0.517
C-8	7.6	1.15	0.529
C-9	8.0	1.23	0.514
C-10	9.6	1.21	0.518
C-11	8.6	1.20	0.543

Table 7 Unstable fracture toughness under different working conditions

It can be seen from above table that K_{IC}^{S} value gets smaller as initial crack-depth ratio increases, so K_{IC}^{S} based on initial crack-depth ratio not only has size effect, but also changes with the changes of initial crack-depth ratio. That indicates that subcritical growth quantity of wedge splitting specimen changes with size, related to initial crack-depth ratio as well, which is different from three-point bending beam. Thus, it is obvious that small specimen has to take stable growth of crack into consideration.

Flexibility coefficient applied in calculating valid subcritical crack growth length (a_c) with double-K fracture criterion is diverse, thereby leading to different a_c. After obtaining a_c, fracture toughness K_{IC}^{S} and CMODc can be figured out, so valid subcritical crack growth length (a_c) is believed to be an important parameter [12-13]. In two-parameter model, because unloading point in test is hard to be controlled in a specified point, valid subcritical crack growth length (a_c) obtained by computer is biased compared with theoretical value. However, double-K fracture criterion is with no need for unloading process and controlling unloading point in test, simply works out valid subcritical crack growth length (a_c) with P_{max} and its corresponding CMODc, and the test results are relatively close to theoretical value.

Ordinary concrete has the same change rule of unstable fracture toughness with RCC. Crack-depth ratio has an effect on the fracture toughness of ordinary concrete and RCC, but there are also differences. The fracture toughness of ordinary concrete decreases as crack-depth ratio increases, and this principle is basically suitable for CRR.

DISCUSSION

It is summarized from analysis of fracture test results of RCC and ordinary concrete wedge-splitting specimens that double-K fracture criterion may have some differences although it is simple, practical and without human distractions. Concrete fracture toughness has size effect, that is to say, concrete fracture toughness increases as size of specimen increases; besides, crack-depth ratio affects concrete fracture toughness to some extent, but the influences are not all consistent. Change rules of unstable fracture toughness of ordinary concrete and RCC are basically the same, and crack-depth ratio plays a role in fracture toughness of ordinary concrete and RCC, but not identical. The rule to ordinary concrete is that concrete fracture toughness is reduced with the increase of crack-depth ratio, and the rule to RCC partially conforms to ordinary concrete rule. In addition, crack-depth ratio of specimen also has a great influence on fracture toughness, and varies non-uniformly; when $a_0 / h < 0.4$, K_{IC}^S increases as a_0 / h rises; it decreases as a_0 / h rises when $a_0 / h > 0.4$, and reaches maximum when $a_0 / h = 0.4$, i.e., unstable value.

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