EXPERIMENTAL INVESTIGATIONS BASED ON THE GRIFFITH-IRWIN THEORY PROCESSES OF THE CRACK DEVELOPMENT IN CONCRETE

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ABSTRACT

The paper presents the results of experimental investigations performed to determine the plain-strain fracture toughness K_{Ic} and critical crack length a_{cr} for concrete as well as to study the relationship between these parameters and differ ent factors, such as the crack length, type and size of aggregate, type of cemer concrete mix composition (by weight), size and type of specimens, age and temperature of specimens being tested.

The aforesaid investigations have revealed the applicability limits of the Griffith-Irwin classic theory and proved that in many cases K_{Ic} is not a constant. The a_{cr} value of the order of the maximum size of aggregate turned out to be more stable and practically independent of certain factors.

KEYWORDS

Concrete; brittle fracture mechanics; opening mode fracture toughness; critical crack length; experiment.

INTRODUCTION

For many years now, the Griffith-Irwin classic theory has been successfully applied to the analysis of fracture process in metals, polymers and silicates. However, the experience in its application to concrete and similar materials gained since the time of publishing the first paper on the problem (Kaplan, 1961) is relatively scarce. The concrete fracture studies from the viewpoint of brittle fracture mechanics are being conducted at the B. E. Vedeneev All-Union Research Institute of Hydraulic Engineering (VNIIG), Leningrad, from 1968 (Khrapkov, Geinats, 1968; Lamkin, Pashchenko, 1972; Pashchenko, Trapeznikov, 1973, 1975; Khrapkov, Trapeznikov and others, 1978). Given below are some results of the experimental investigations undertaken at the VNIIG over 1975-79.

One of the main problems to be solved when applying the Griffith-Irwin theory to concrete for practical purposes is the determination of actual values of the opening mode fracture toughness K_{Ic}. For this end and in order to determine the relationship between this characteristic and various factors about 3000 of specimens were subjected to tests. The tested specimens differed in type of cement (portland cement, portland blast furnace cement), type of aggregate (gravel, crushed stone), size of aggregate (max. size of aggregate d_{max} was 5, 10, 20, 30, 40, 60, 80, 100 mm), type of specimens (the cylinder with a notch in the plane of compressive forces; the centrally tensioned specimen with a single-edge notch; the tensioned prism with a central notch normal to the line of forces). They also differed in age, size and temperature at the moment of testing. Besides the concrete and sand-cement mortar specimens the cement stone specimens were tested. As a rule, the ratio between d_{max} and the linear size of a specimen did not exceed 0.1. Most of the specimens were large in size. Specifically, 904 cylinders were tested, out of which 24 were 100 cm in diameter and 75 cm in height; the other 37, 292, 262 and 289 cylinders were 60 cm, 40 cm, 20 cm and 10 cm, respectively, both in diameter and height.

RELATIONSHIP BETWEEN FRACTURE TOUGHNESS AND CRACK LENGTH

Knowing the crack length a and maximum stresses in the notched specimen σ_{ult} (these stresses are calculated from the ultimate load in the same manner as for the specimens without a notch) the K_{Ic} value can be determined by the formula:

$$K_{Ic} = \sigma_{ult} \sqrt{D}\ f\left(\frac{a}{D}\right) \qquad (1)$$

where D is the linear size of the specimen and f is the dimensionless function which depends on the specimen configuration and the scheme of its loading.

The artificial cracks (notches) were made with the help of 0.15-0.25 mm thick oiled foil. Figure I shows the relationship between K_{Ic} and the crack length a.

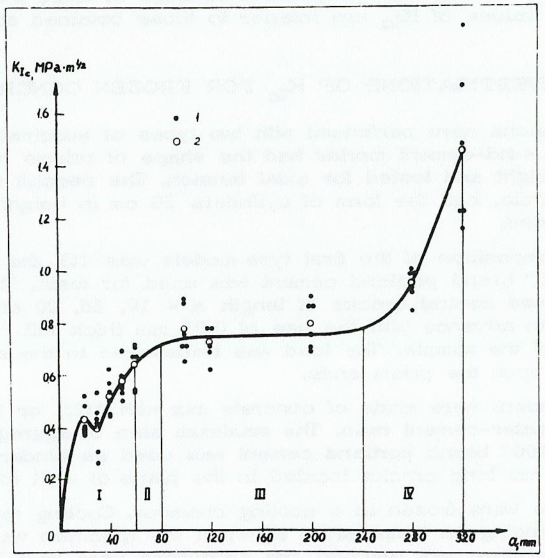

Fig. 1. Relationship between K_{Ic} and the crack length a for cylinder specimens with 40 cm diameter: 1-experimental points; 2-arithmetical means.

The tested specimens were concrete cylinders of 40 cm diameter and height aged for 28 days; the maximum size of the aggregate (crushed stone) was d_{max}=40 mm; the "400" brand portland cement was used as a binder; the cylinders were manufactured of 1:1.8:4.2 concrete mix (by weight) having the water-cement ratio 0.5; the crack length was taken as a = 20, 30, 40, 50, 60, 100, 120, 200, 280, 320 mm.

The diagram given in Fig. 1 can be divided into several characteristic portions. At initial portion I (its length is of the order of d_{max}) the specimen behaviour does not follow the Griffith-Irwin theory regularities. If the crack length is less than the length of this portion, the stable growth of the crack to the boundary point between portions I and II is likely to take place prior to spontaneous rupture of the specimen.

Portion II can be considered as a domain of the Griffith-Irwin theory, but with varying fracture toughness. If the crack length falls within this portion, the crack growth gets unstable from the very beginning.

Portion III starts at a crack length a, equal to about (2-2.5) d_{max}. Within this portion the K_{Ic} (a) curve tends to become a horizontal straight line. This is the domain of the crack theory classic version (the linear fracture mechanics). The length of portion III in our case amounts to 40% of the specimen diameter.

The testing of the cylinders having relatively long cracks made it possible to distinguish one more portion (IV) where the K_{Ic} value increases again.

Figure 2 illustrates the relationship K_{Ic} (a) for the specimens in the form of prisms of 10 cm height and 5x5 sq cm cross section with internal cracks. The prisms were made of 1:3 sand-cement mortar with the water-cement ratio 0.53; the maximum size of the aggregate (sand) was d_{max} = 5 mm. The "500" brand portland cement and "300" brand portland blast furnace cement were used as binders.

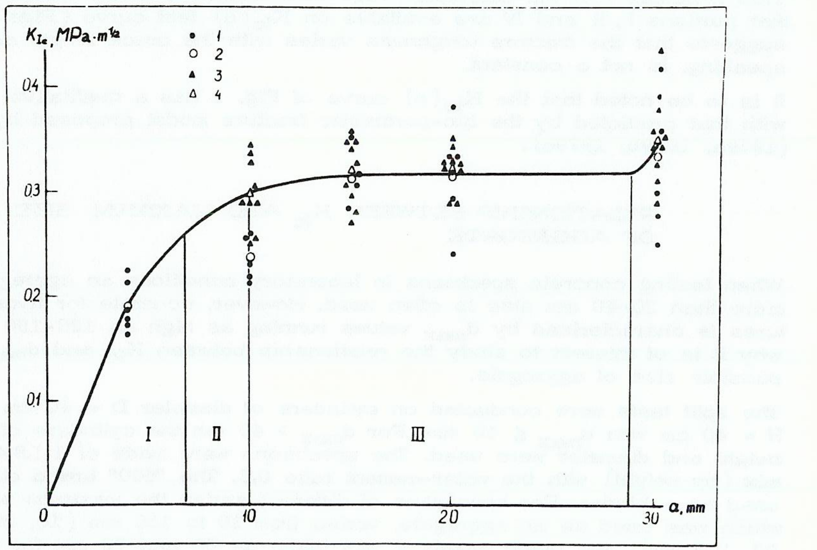

Fig. 2. Relationship between K_{Ic} and the central notch length a for prismatic specimens of 5x5 cm^2 section and 10 cm height: 1-experimental points for specimens with portland cement; 2-arithmetical means for specimens with portland cement; 3-experimental points for specimens with blast furnace portland cement; 4-arithmetical means for specimens with blast furnace portland cement.

By the time of testing the age of specimens prepared with portland cement and portland blast furnace cement was 90 days and 180 days, respectively. The artificial crack length a was taken as 5, 10, 15, 20 and 30 mm. As it is seen from Fig. 2 at a/D 0.6 the $K_{Ic}(a)$ diagram is similar to that in Fig. 1. At portion I, however, the abnormal behaviour of specimens with small a-values is caused in this case by some other reasons: the specimens collapse most probably due to the formation of initial surface cracks since they prove to be more sensible to structure surface defects than to central notches. That is why the K_{Ic} value determined for the specimen with a small central notch is to be considered as a conventional value.

The K_{Ic} values at portion III are of major practical interest. The limits of the domain governed by the laws of linear fracture mechanics can be determined directly, based on the notched specimen strength values without defining K_{Ic}. From formula (1) it follows that at K_{Ic} = const

$$\frac{\sigma'_{ult_1}}{\sigma'_{ult_2}} = \frac{f\left(\frac{a_2}{D}\right)}{f\left(\frac{a_1}{D}\right)} \qquad (2)$$

Compared in the above formula are two specimens equal in size and having notches of length a_1 and a_2 and strength σ'_{ult_1} and σ'_{ult_2}. The validity of relationship (2) can be illustrated by the following example. For two cylinders containing 100 and 200 mm notches (Fig. 1) the strength ratio calculated by formula (2) is equal to 1.80. The test arithmetical mean is 1.75, the confidence interval of mean values varying from 1.66 to 1.84 at the confidence limit 95%. This indicates that the calculated ratio falls within the above interval. The fact that portions I, II and IV are available on $K_{Ic}(a)$ test curve (Figs 1 and 2) suggests that the fracture toughness varies with the crack length and, generally speaking, is not a constant.

It is to be noted that the $K_{Ic}(a)$ curve of Fig. 1 has a qualitative agreement with that predicted by the two-parameter fracture model proposed by Trapeznikov (1979a, 1979b, 1979c).

RELATIONSHIP BETWEEN K_{Ic} AND MAXIMUM SIZE OF AGGREGATE

When testing concrete specimens in laboratory conditions an aggregate of not more than 20-40 mm size is often used. However, concrete for hydraulic structures is characterized by d_{max} values running as high as 120-150 mm. That is why it is of interest to study the relationship between K_{Ic} and d_{max} at maximum possible size of aggregate.

The split tests were conducted on cylinders of diameter D = 40 cm and height H = 40 cm with $d_{max} \leqslant 40$ mm. For $d_{max} > 40$ mm the cylinders of 60 cm height and diameter were used. The specimens were made of 1:1.8:4.2 concrete mix (by weight) with the water-cement ratio 0.5. The "500" brand cement was used as a binder. For specimens of different series the maximum size of gravel, which was used as an aggregate, varied from 10 to 100 mm (10, 20, 30, 40, 60, 80, 100 mm). The notch length a was taken as 60 and 70 mm for d_{max}=10 mm; 40 and 80 mm - for d_{max} = 20 mm; 60 and 80 mm - for d_{max} = 30 mm; at d_{max} = 40, 60, 80, 100 mm the notch length was 30, 150, 200 and 250 mm, respectively. The age of specimens at the moment of testing was 3 months; the total amount of specimens numbered 51. The values of K_{Ic} were obtained from (1). The K_{Ic}/d_{max} dependence diagram is presented in Fig. 3. It is evident from the diagram that for concrete of constant weight composition and water-cement

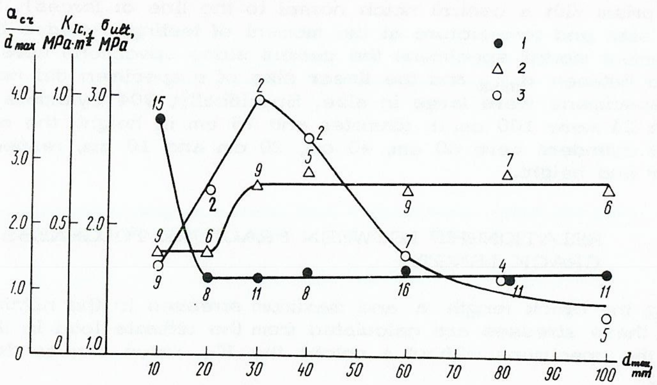

Fig. 3. Relationship between the parameters of concrete and the maximum size of aggregate (arithmetical means) (figures on curves denote numbers of specimens): 1 - a_{cr}/d_{max}; 2 - K_{Ic}; 3 - σ_{ult}.

ratio the values of K_{Ic} are independent of d_{max} at $d_{max} \geqslant 30$ mm. At $d_{max} <$ 30 mm the values of K_{Ic} are inferior to those obtained at $d_{max} \geqslant 30$ mm.

INVESTIGATIONS OF K_{Ic} FOR FROZEN CONCRETE

The investigations were performed with two types of specimens. The first type specimens of sand-cement mortar had the shape of prisms of 5x5 sq. cm section and 10 cm height and tested for axial tension. The second type specimens were made of concrete, had the form of cylinders 20 cm in height and diameter and were split tested.

The weight composition of the first type models was 1:3, the water-cement ratio - 0.53; the "500" brand portland cement was used for tests. The major part of prisms contained central cracks of length a = 10, 15, 20 and 30 mm. The cracks were formed in advance with the use of 0.05 mm thick foil normally to the longitudinal axis of the sample. The load was transferred to the sample through metal plates, glued upon the prism ends.

The test cylinders were made of concrete mix with 1:2:1 or 1:2:3 weight composition and 0.5 water-cement ratio. The maximum size of aggregate (gravel) was 20 mm; the "400" brand portland cement was used as binder. Part of the samples contained 60 mm long cracks located in the plane of split forces.

The specimens were frozen in a cooling chamber. Cooling rate varied within 2-7°C/hr depending on temperature to which the specimen was cooled. After the required temperature was reached, the specimens were kept in a cooling chamber at the prescribed temperature for up to 3 hours.

The prisms were tested at temperatures -4°C, -12°C, -20°C, and -27°C and the cylinders - at temperature -20°C.

For comparison the specimens of both types were also tested at a above zero temperature (+20°C). The moisture content of the specimens was approximately 4% by weight. As a whole 328 prisms and 60 cylinders were tested.

Figure 4 presents the values of K_{Ic} for the prisms tested at the age of 28 days.

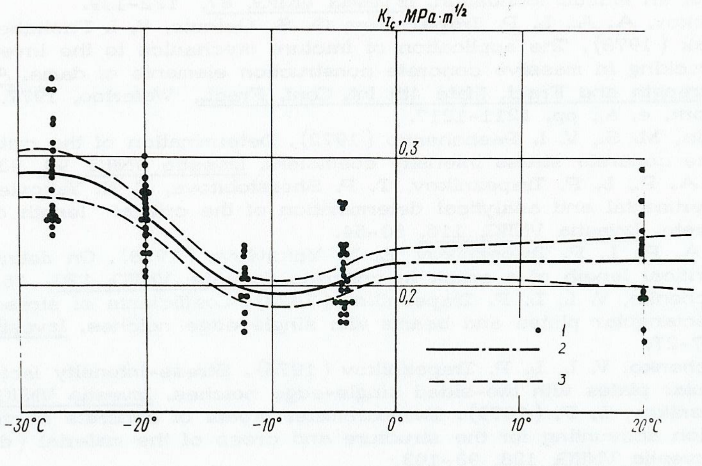

Fig. 4. Relationship between K_{Ic} and temperature of specimens during testing: 1-experimental points; 2-arithmetical means; 3-confidence intervals of arithmetical means at 95% confidence.

Besides the experimental points and arithmetical means of K_{Ic} the limits of their confidence intervals obtained for the 95% confidence level are also given. According to the diagram the decline of temperature to -4°C, then to -12°C results in some decrease in the critical value of the plane strain fracture toughness, but further cooling to -27°C brings about the 30-45% rise of K_{Ic}. Table 1 summarizes the data obtained on the cylinders tested at the age of 90 days.

It follows from the Table that the values of K_{Ic} as well as $\sigma_{ult} = R_{split}$ (ultimate stress obtained on specimens without a notch) cannot be regarded as constants of concrete. Similarly to the case of sand-cement mortar, the values of the above parameters for cylinders tested at sub-zero temperatures exceed the same values for cylinders tested at above zero temperatures. They show considerable change with the variation in concrete weight composition. It should be also noted that the K_{Ic}/σ_{ult} ratio is practically invariant with respect to the weight composition of concrete mix.

EXPERIMENTAL AND ANALYTICAL ESTIMATION OF CRITICAL LENGTH OF A CRACK IN CONCRETE

According to the present-day concepts, fracture of concrete in tensile tests initially assumes the character of microcracking; this is a steady process which leaves the mechanical behaviour of a specimen unaltered. At a certain stress level, however, the development of macrocracks is observed in the specimens. Under certain loads this process may become unsteady and lead to a complete failure of specimens. The crack length at which the load increase would result in spontaneous failure may be regarded as critical length a_{cr} of a crack in a concrete specimen.

Compare two identical specimens with and without a notch, assuming that the values of K_{Ic} at the tip of a notch of length a and at the tip of a natural crack of length a_{cr} are equal. The following expression (Pak, Trapeznikov and others, 1977, 1978) can be received from (1):

$$a_{cr} = D f^{-1} \left[\frac{\sigma'_{ult}}{\sigma_{ult}} f\left(\frac{a}{D}\right) \right] \tag{3}$$

Figure 5 presents the calculation results obtained in accordance with (3) for cylinders of 40 cm diameter. The tip of a notch of length a was located within Portion III (Fig. 1). In tests d_{max} varied from 20 to 100 mm. The number of experimental points (with d_{max} = 20, 30, 40, 60, 80, and 100 mm) was 56, 11, 8, 16, 11 and 11, respectively.

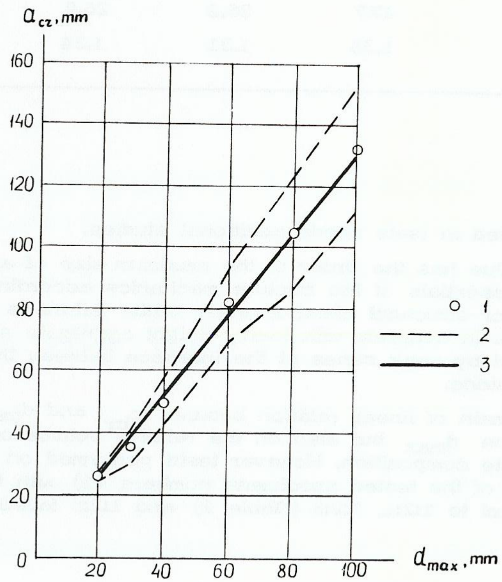

Fig. 5 Relationship of a_{cr} and the maximum size of aggregate d_{max}: 1-arithmetical means; 2-confidence intervals of arithmetical means at 95% confidence; 3-straight line $a_{cr} = kd_{max}$.

The test data treated statistically indicate that close correlation exists between a_{cr} and d_{max}. The regression equation can be approximated by the expression:

$$a_{cr} = k\, d_{max} \tag{4}$$

in which k = 1.32 at the kind of aggregate utilized.

Thus, for the specimens with aggregate 20 mm $\leqslant d_{max} \leqslant$ 100 mm the critical crack length is proportional to d_{max} and exceeds this value to some extent. It means that the a_{cr}/d_{max} ratio is practically independent of the maximum size of aggregate. This can be also seen from Fig. 3 in which the dependence of a_{cr}/d_{max} on d_{max} is presented. Note that the dependence between a_{cr} and d_{max} stops to be linear at d_{max} = 10 mm.

TABLE 1

Parameters of concrete	Weight composition of concrete mix and temperature			
	1:2:1		1:2:3	
	T= -20°C	T= +20°C	T= -20°C	T= +20°C
R_{split}, MPa	2.94	2.10	2.61	1.79
K_{Ic}, MPa·m½	0.65	0.49	0.57	0.39
K_{Ic}/R_{split}, mm½	7.0	7.30	6.90	6.90
a_{cr}, mm	27.7	26.2	26.9	26.7
a_{cr}/d_{max}	1.38	1.31	1.34	1.33

This phenomenon observed in tests needs additional studies.

The fact that the a_{cr} value has the order of the maximum size of aggregate closely corresponds to the essentials of the fracture mechanics according to which the strength of a specimen or structural element under brittle failure is governed by the maximum defect size. In concrete with heavy-weight aggregate such defects are primarily represented by weak zones at the interface between the aggregate grains and the cement stone.

Coefficient k in the domain of linear relation between a_{cr} and d_{max} seems to be dependent not only on d_{max} but also on the relative volume of large-size aggregate in the concrete composition. However tests performed on cylinder specimens (the total amount of the tested specimens numbers 41) with the weight composition of concrete equal to 1:2:1, 1:2:3 (Table 1) and 1:2:5 failed to reveal this dependence.

SUMMARY AND CONCLUSIONS

The investigations of cracking development in concrete in the light of classical Griffith-Irwin theory permit to establish a number of principles characteristic of the process, the dependence between a_{cr} and d_{max} being one of most important features. However, the assumption of the constancy of the parameter K_{Ic} which, according to the Irwin-Griffith theory, defines the resistance of material to crack propagation was not supported in a number of practically important cases. Thus, K_{Ic} proved to depend on the crack length, the specimen temperature during testing and the concrete weight composition.

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