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RILEM DRAFT RECOMMENDATIONS
PROJETS DE RECOMMANDATION DE LA RILEM

TC 89-FMT FRACTURE MECHANICS OF CONCRETE - TEST METHODS
MÉCANIQUE DE LA RUPTURE DU BÉTON - MÉTHODES D'ESSAI

Determination of fracture parameters (K_{Ic}^s and $CTOD_c$) of plain concrete using three-point bend tests

The text presented hereunder are drafts which are being submitted to enquiry. Comments should be sent to Prof. S. P. Shah, The Technological Institute, Northwestern University, Evanston, Illinois 60208-3109, USA, before 1 July 1991.

CONTENTS

1. SCOPE

This recommendation covers the determination of the critical stress intensity factor K_{Ic}^s and the critical crack tip opening displacement $CTOD_c$ of mortar and concrete, using three-point bend tests on notched beams. The critical stress intensity factor is defined as the stress intensity factor calculated at the critical effective crack tip, using the measured maximum load. The critical crack tip opening displacement is defined as the crack tip opening displacement calculated at the original notch tip of the specimen, using the measured maximum load and the critical effective crack length.

The critical stress intensity factor and the critical crack tip opening displacement, along with the Young's modulus E, are sufficient to characterize the fracture resistance and energy dissipation of concrete and mortar.

2. SPECIMENS

2.1 Dimensions

The specimen dimensions as indicated in Fig. 1 are given in Table 1 for aggregates not larger than 50 mm (2 in.).

A saw-cut notch or a pre-cast notch shall be made, with the width of the notch less than 5 mm. The initial notch-to-depth ratio (a_0/d) shall be equal to 1/3. A minimum of four specimens are required for each type of material.

If the maximum size of aggregate is larger than 50 mm, the specimen dimensions shall be increased proportionally and the span-to-depth ratio shall be kept equal to 4.

2.2 Fabrication of specimens

After casting, the specimens shall be covered with wet burlap or kept in the curing room with 100% relative humidity at 23 ± 2°C for the first 24 h. On the second day all the specimens shall be transferred to the curing room until about 4 h before testing.

3. APPARATUS

A closed-loop testing machine with the crack mouth opening displacement (CMOD) as the feedback signal or a relatively stiff machine is required to achieve a stable failure. The crack mouth opening displacement and the applied load shall be recorded continuously

Table 1 Dimensions of specimens

D_{max} (mm)	Depth, d (mm)	Width, b (mm)	Length, L (mm)	Span, s (mm)
1 to 25	150 ± 5	80 ± 5	700 ± 10	600 ± 5
25.1 to 50	250 ± 5	150 ± 5	1100 ± 10	1000 ± 5

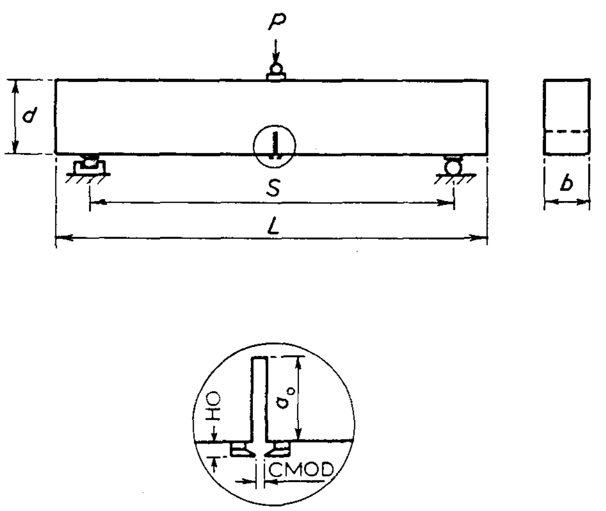

Fig. 1 Testing configuration and geometry of specimen. P = load, L = specimen length, S = specimen loading span, d = beam depth, b = beam thickness, HO = thickness of holder of clip gauge, a_0 = initial notch depth, CMOD = crack mouth opening displacement.

during the test. A clip gauge is recommended to measure the CMOD. However, if a clip gauge is not available, an LVDT can be used as a replacement. To avoid possible errors caused by the bending effect, the gauge length of the LVDT shall be kept as small as possible. The CMOD shall be measured at the centre of the notch to minimize possible errors caused by eccentricity.

The supports and the loading arrangements shall be such that the applied forces acting on the beam are statically determinate.

4. TEST PROCEDURE

4.1 Control of loading

The rate of loading shall be controlled by a constant rate of increment of crack mouth opening displacement (or load-line deflection) such that the peak load is reached in about 5 min.

4.2 Loading and unloading requirement

The applied load is manually reduced (also termed unloading) when the load passes the maximum load and is at about 95% of the peak load (Fig. 2). When the applied load is reduced to zero, reloading is applied. The rate of unloading and reloading does not have to be the same as the initial loading rate, and each loading and unloading cycle shall be finished in about 1 min. Only one cycle of loading–unloading is required for the test.

5. TEST RESULTS AND CALCULATIONS

A typical test result (i.e. a load–CMOD curve with several loading–unloading cycles) is shown in Fig. 2. Based on the load–CMOD curve, the Young's modulus E, the critical stress intensity factor K_{Ic}^{s}, and the critical crack tip opening displacement $CTOD_c$ can be determined.

5.1 Young's modulus, E

The Young's modulus E is calculated from the equation

$$E = 6S\, a_0 V_1(\alpha)/[C_i d^2 b] \qquad [\mathrm{N\ m^{-2}}] \tag{1}$$

in which C_i is the initial compliance calculated from the load–CMOD curve (Fig. 2) [m N^{-1}]; also

$$V_1(\alpha) = 0.76 - 2.28\alpha + 3.87\alpha^2 - 2.04\alpha^3 + \frac{0.66}{(1-\alpha)^2} \tag{2}$$

where $\alpha = (a_0 + HO)/(d + HO)$ and S, a_0, HO, d and b are defined in Fig. 1.

5.2 Critical effective crack length, a_c

The critical effective crack length a_c [m] ($a_c = a_0 +$ stable crack growth at peak load) is determined from the Young's modulus E calculated from Equation 1 and the unloading compliance C_u measured at the maximum load (Fig. 2). Using an iteration process, the critical effective crack length a_c is found when Equation 3 is satisfied:

$$E = \frac{6S\, a_c V_1(\alpha)}{C_u d^2 b} \tag{3}$$

in which a_c = the critical effective crack length to be determined [m], $\alpha = (a + HO)/(d + HO)$, and C_u = the unloading compliance at 95% of peak load [m N^{-1}].

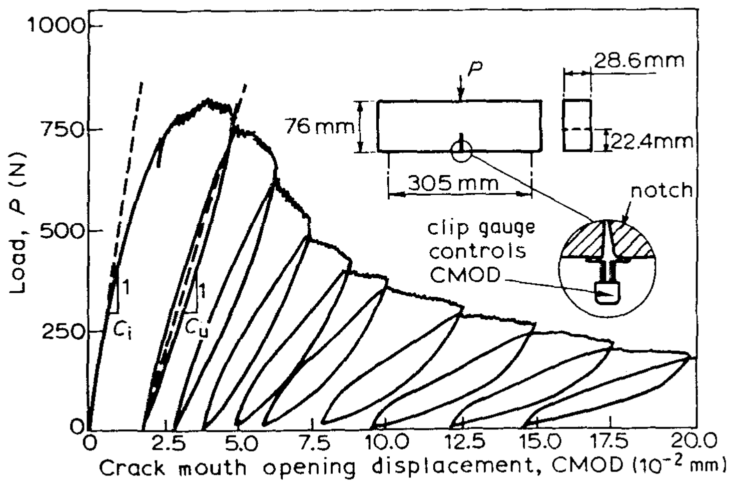

Fig. 2 Typical experimental load–CMOD plot. Mortar mix = C:S:A:W = 1.0:2.6:0.0:0.65.

5.3 Critical stress intensity factor, K_{Ic}^s

The critical stress intensity factor is calculated using the equation

$$K_{Ic}^s = 3(P_{max} + 0.5W)\frac{S(\pi a_c)^{1/2}F(\alpha)}{2d^2 b} \quad [\mathrm{N\ m^{-3/2}}] \qquad (4)$$

in which

$$F(\alpha) = \frac{1.99 - \alpha(1-\alpha)(2.15 - 3.93\alpha + 2.7\alpha^2)}{\sqrt{\pi}^{1/2}(1+2\alpha)(1-\alpha)^{3/2}}$$

where $\alpha = a_c/d$, P_{max} = the measured maximum load [N], $W = W_0 S/L$ [N], and W_0 = self-weight of the beam [N].

5.4 Critical crack tip opening displacement, $CTOD_c$

The critical crack tip opening displacement is calculated using the equation

$$CTOD_c = \frac{6P_{max} S a_c V_1(\alpha)}{Ed^2 b}$$

$$[(1-\beta)^2 + (1.081 - 1.149\alpha)(\beta - \beta^2)]^{1/2} \quad [\mathrm{m}] \qquad (5)$$

in which $\alpha = a_c/d$ and $\beta = a_0/a$.

For those laboratories which cannot perform a stable three-point bend test, C_u values can be approximately calculated by assuming that the unloading path will return to the origin. The values of K_{Ic}^s and $CTOD_c$ determined based on this assumption are about 10 to 25% higher than the values calculated using the actual unloading compliance.

6. REPORT

The report shall include the following:

1. Specimen dimensions, weight of specimen, mix-proportion, number of specimens tested, and date of test.
2. Complete load–CMOD curve, peak load P_{max}, initial compliance C_i and unloading compliance C_u for each specimen.
3. Young's modulus E, critical effective crack length a_c, critical stress intensity factor K_{Ic}^s, and critical crack tip opening displacement $CTOD_c$ for each specimen.
4. Special events occurring during each test.

7. BACKGROUND

With these two parameters it is possible to predict the maximum load of a specimen or a structure of any arbitrary geometry [1–3]. A crack of given length (a_0, which can be equal to zero) will critically propagate when it reaches a critical effective crack length a_c. To determine a_c two fracture parameters are needed: K_{Ic}^s and $CTOD_c$. The sub-committee on Mode I testing of RILEM 89-FMT has examined test results for a large number of notched beams of varying dimensions, and concluded that these two parameters can be considered as valid material parameters [4].

This testing method is unique in that all material properties (i.e. K_{Ic}^s, $CTOD_c$ and E) can be determined from a single test performed on a notched beam specimen. As a result, the application of these material parameters to the associated effective crack model (i.e. the two-parameter fracture model [1]) is self-consistent. Using these two parameters and the Young's modulus, it is also possible to predict the critical load under mixed-mode loading conditions [2] as well as for compact-tension and wedge-loaded cubical specimens [5].

The critical crack extension obtained from these two parameters has been shown to decrease with an increase in concrete strength and with an increase in rate of loading [6, 7]. Thus, these two parameters well represent the fracture response of quasi-brittle materials like concrete. A geometry-dependent R-curve approach can also be predicted by using these two parameters [8]. It should be noted that Llorca *et al.* [9] have shown that the size effects predicted by this proposed two-parameter fracture model are quite comparable with the results predicted by the accompanying proposed size-effect law.

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