INFLUENCE OF MOISTURE ON CRACKING PROCESSES IN CONCRETE

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An experimental study shows that the presence of free water in a microconcrete makes its fracture toughness (K_{Ic} in linear fracture mechanics) dependent on crack velocity, leading to the conclusion that a wet concrete does not have an intrinsic fracture toughness even under quasi-steady crack propagation conditions.

INTRODUCTION

An investigation at the Laboratoire Central des Ponts et Chaussées (LCPC) of the influence of crack velocity on the fracture toughness of a concrete (Rossi (1)) has shown that these two parameters are highly interdependent. The author of the study put forward the hypothesis that this interdependence is related to the presence of free water (not chemically bonded) in the concrete (an hypothesis suggested by the well-known fact that practically all time- dependent physical phenomena in concrete are related to the presence of free water). Our aim was to test the soundness of this hypothesis by carrying out an experimental study in which crack velocity was made to vary in microconcrete specimens in two different internal moisture states: initial free water contents of 100 % and 0 %.

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BRIEF REVIEW OF FRACTURE MECHANICS AND ITS APPLICATION TO CONCRETE

All common materials (metals, concretes, ceramics, etc.) have an inelastic zone (dislocations, microcracks, etc.) at the crack tip during crack propagation. Barenblatt (2) has proposed a model that can be used to apply linear fracture mechanics to these real materials. He shows that if the nonlinear zone at the crack tip is confined (i.e. very small with respect to the elastic domain that surrounds it) and independent at the time of crack growth (the shape of the critical nonlinear zone must be independent of the loading and geometry of the cracked structure),the K_{Ic} determined (fracture toughness of the material) is in fact an intrinsic property of the material (independent of the type of test carried out and of the crack length). So it is known only after the fact whether an experiment has created conditions under which linear fracture mechanics is applicable (K_{Ic} must remain constant during crack growth).

Application to concrete

In the case of concrete, many researches have shown that the nonlinear zone (microcracked in the present case) depends on the largest grain size. To suggest an order of magnitude, studies carried out at the LCPC (Rossi (3)) on common structural concretes in which the largest grain size is about 20 mm have shown that cracking tests must be performed on very large specimens - of the order of a few metres - to satisfy the conditions of applicability of linear fracture mechanics mentioned above.

EXPERIMENTAL METHODOLOGY

Since the objective of our study was to carry out a large number of cracking tests under varied conditions of crack propagation velocity (6 velocities were planned) and internal moisture content (initial free water contents of 100 and 0 %), it was obviously impractical to conduct the tests on such large specimens. We therefore chose to work with small rectangular specimens, notched (to initiate cracking), under a three-point bending load - a standard test in linear fracture mechanics. Figure 1 shows the specimen used and experimental arrangements.

The need to have a largest grain size that was very small with respect to the specimen size, so as to confine the zone of microcracking (see above), led us to choose a microconcrete having no inclusions larger than about 2 mm.

To ensure stable crack propagation (essential for determining the intrinsic K_{Ic} of the material), we conducted the test at constant crack opening rate. This was done using a displacement sensor on the bottom fibre of the specimen, spanning the initial notch (figure 2).

A strain gauge is used to measure deflection without including the yielding at the bearings (Boulay (4)) (figure 1). This deflection measurement is an essential item of information in the method of calculation used to determine the values of K_{Ic}, as we shall see later.

To obtain six crack propagation velocities at each concrete moisture content, we chose to vary the imposed notch opening rate. We shall see later how the crack propagation velocity in the course of the test is determined.

The concrete was investigated at two moisture contents, 0 and 100 % initial free water. At each moisture content, six different notch opening velocities were examined: 0.002, 0.01, 0.025, 0.05, 0.2, and 2 mm/min. Finally, three tests were carried out at each notch opening velocity to give an idea of the dispersion of the results, so a total of 36 specimens were tested in the course of the study.

All the specimens were protected against desiccation (exchanges of moisture with the exterior) by a film of self-adhesive aluminium bonded to the surface of the specimen. This precaution assures good control of the internal moisture content of the concrete, which remains homogeneous in the specimen in the course of the tests.

METHOD OF CALCULATION OF KIC

There are various equivalent expressions for K_I; among them, we chose the one associated with the compliance method. This method, standard in fracture mechanics (Bui (5)), makes it possible to determine the fracture toughness of a material based solely on changes in the compliance of the concrete during crack propagation.

The main difficulty encountered in applying this method to concrete is in monitoring the crack to determine its length: it is now well known (Bascoul et al (6), Rossi (7)) that the part of a crack visible at the surface is not representative of its position in the core, and thus that the standard optical methods routinely used when fracture mechanics is applied to metals are not applicable to concrete. We are therefore led to introduce the concept of effective crack a_e (also called imaginary or equivalent), which is determined as follows: during crack propagation, we apply loading-unloading cycles, making it possible to track the evolution of the experimental compliance of the specimen, and we compare these experimental compliance values with the expression for the theoretical compliance versus crack length yielded by numerical analysis using the finite- element method. By this means we determine an effective crack length that in fact represents the idealized crack mechanically equivalent to the real crack (in terms of flexibility of the specimen).

Determining the mean effective-crack propagation velocity ($\dot{a}_e$) then becomes trivial, since, experimentally, all the parameters (force, notch opening, sag) are recorded versus time. It then suffices to take, in the course of a test, two effective crack lengths that bound a domain in which the value of K_{IC} was found to be constant and to divide the difference between the two lengths by the corresponding time difference.

RESULTS

Figure 3 shows all results in the form of a K_{IC} versus log $\dot{a}_e$ diagram. Also plotted on this figure are the curves joining the points representing the mean on both axes of the values for each group of three specimens for each crack opening velocity.
In the range of crack propagation velocities explored, this curve elicits the following remarks and conclusions:

1. Crack propagation velocity has no significant influence on the K_{IC} of the totally dry concrete, but a clear influence on that of the wet concrete. This variation of K_{IC}, which is of the order of 25 % in our study, is greater than the dispersion (resulting from the material and the testing conditions) of each group of three points for the three tests carried out at each notch opening velocity. It should also be noted that the dispersion on the wet specimens is close to that on the dry specimens.

It may therefore be concluded that is is indeed the presence of free water in the microconcrete that explains this velocity dependence.

2. The completely dry concrete has an intrinsic K_{IC}, whereas the damp concrete does not, strictly speaking, have an intrinsic fracture toughness as defined in linear fracture mechanics.

3. The initial drop of K_{IC} observed in the (K_{IC} versus Log $\dot{a}e$) curve for the wet concrete may seem, in theory, shocking. We think that it can be explained by the fact that the participation of water in the concrete cracking process involves different physical mechanisms, having opposite effects on the cracking process, at different crack propagation velocities. Thoughts about these mechanisms, leading to the start of an explanation of the reduction of K_{IC}, have already been proposed in a previous article (1).We shall summarize them here.

The pores of the concrete contain both liquid water and water vapour, meaning that there are menisci of water. These menisci induce surface tensions that prestress the solid skeleton (producing "endogenous" shrinkage). When a macro- or micro-crack suddenly appears in the concrete, it creates instantaneous voids that may be compared to hygral shocks to the medium. There are therefore movements of water from the pores to the cracks, leading to changes of state - from liquid to vapour, in the pores near the cracks. The net effect of these physical mechanisms is a loss of liquid water in the pores surrounding the cracks, and thus an increase in the prestress of the solid skeleton in these zones (the smaller the menisci, the larger the surface tensions). It should also be noted that these changes of state are accompanied by a temperature drop in these zones, which adds to the prestress of the solid skeleton and thus to the apparent fracture toughness of the material. In consequence, the lower the crack propagation velocity, the greater the effect of the mechanisms just described (the kinetics of crack propagation must be on the same time scale as the diffusion of the water vapour), and vice versa. We think that these effects can explain the initial drop in the K_{Ic} of the wet concrete. On the other hand, at higher crack propagation velocities, the increase in the fracture toughness of the damp concrete is more like familiar dynamic effects on materials in general. The influence of the presence of free water on this evolution is now being investigated.

To conclude, it is to be expected that the change in the evolution of K_{Ic} versus crack propagation velocity (minimum value of K_{Ic}) occurs at a velocity at which the influence of the diffusion of water vapour becomes negligible.

CONCLUSIONS

This experimental investigation has yielded the following result: the presence of free water in a concrete has a significant influence on the cracking behaviour of the concrete. Failure to take the time parameter explicitly into account in modelling this behaviour may result, in our opinion, in a rather crude approximation.

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REFERENCES

(1) Rossi, P., Materials and Structures, vol. 22, 1989, pp. 91-97.

(2) Barenblatt, D.I., "Advance in applied mechanics", Academic Press, 1962, pp. 55-129.

(3) Rossi, P., "Fissuration du béton: du matériau à la structure. Application de la mécanique linéaire de la rupture", Thèse de l'Ecole Nationale des Ponts et Chaussées, 1986 (in french).

(4) Boulay, C., "Conception et préparation d'un essai sur l'étude du couplage entre ténacité et teneur en eau du béton", Mémoire d'ingénieur D.P.E., 1988.

(5) Bui, H.D., "Mécanique de la rupture fragile", Masson, 1978.

(6) Bascoul, A., Kharchi, F., Maso, I., Proceedings of the International Conference on fracture of concrete and rock, Houston, 1987.

(7) Rossi, P., Materials and Structures; vol. 22, 1989, pp. 374-384.

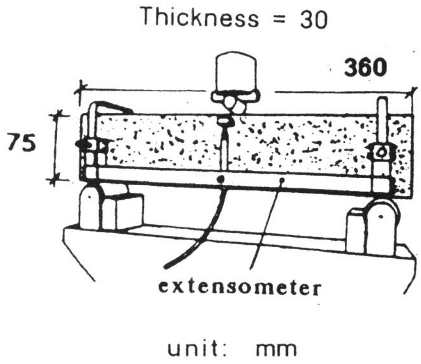

Figure 1 Specimen and experimental testing

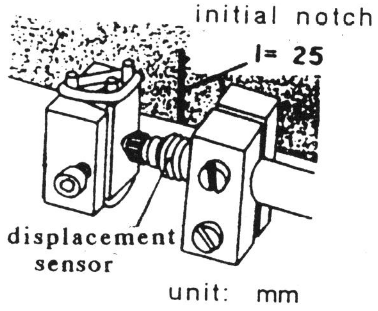

Figure 2 Crack opening measurement

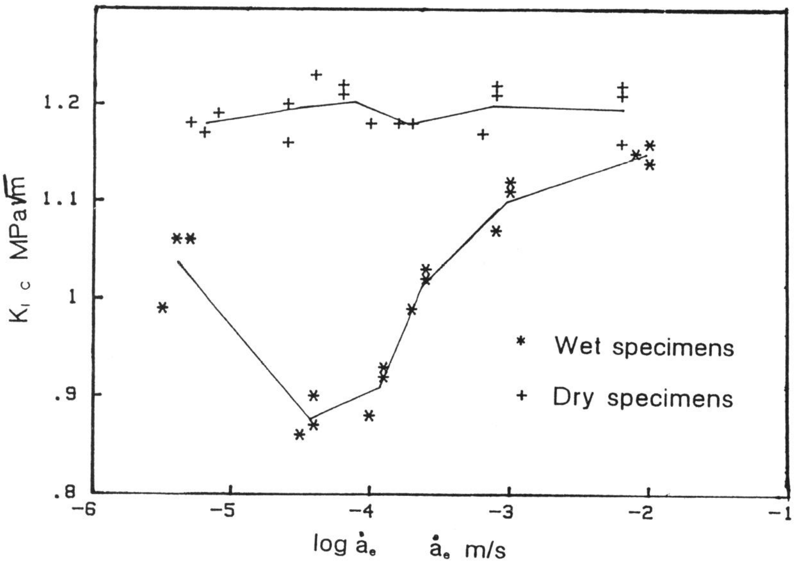

Figure 3 (K_{Ic}, Log $\dot{a}_e$) curves for the two hygral situations