Fracture Resistance Testing of Concrete and Rocks

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INTRODUCTION

Interest in the strength and deformation characteristics of concrete and rocks has increased very much in recent years because they are directly applicable to the design of large concrete structures, particularly for those which must withstand severe loadings generated by traffic, wind, thermal shocks and earthquakes, and also to studies of rock mining, tunnelling, drilling, cutting, crushing, blasting and sometimes indirectly applicable to consideration of the behaviour of large jointed rock masses. This is also due to the need for an understanding of concrete responses as a structural material to various types of loading, and because nonlinear fracture mechanics has entered the field as an aid to understanding concrete damage and failure. In addition, techniques for numerical analysis, such as finite element methods have been developed which require comprehensive material models.

Many types of tests have been devised, using equipment and techniques that range from the crude and empirical, with results that are almost impossible to interpret analytically, to the theoretically elegant, which are almost impossible to execute practically.

The greatest difficulty in the direct test for the determination of tensile strength and shear strength of concrete is the gripping of specimens. To achieve uniform tensile stress distribution or well defined shear stress, and for easy gripping, especially prepared specimens are required which are difficult to make. As a result, a great number of indirect methods have been developed for determining tensile and shear strengths of concrete and rock materials (Hawkes & Mellor, 1970, Roberts, 1977 and Lama & Vutukuri, 1978).

UNIAXIAL TENSILE STRENGTH

Tensile strength of concrete and rock materials is one of its most fundamental and important properties, particularly because these materials are brittle and very much weaker in tension than in compression.

The interest of tensile strength of concrete has increased very much in recent years for many reasons : (1) its role in bending and punching shear has been recognized, (2) it is one of the relevant parameters in the mechanical behaviour of reinforced concrete, (3) it is required for the design of pavements, for the analysis of concrete dams to prevent thermal cracking and sometimes for the design of prestressed beams, (4) it is also of interest in determining the initiation of cracking in plain and reinforced concrete members, (5) techniques for numerical analysis need comprehensive material models, and (6) structures are being built in harsh environments where temperature variations play a major role with regard to durability and where cracking of concrete must be controlled.

In spite of this need for an accurate knowledge of tensile strength, a complete satisfactory tensile test for building materials has not so far been developed. The determination of concrete tensile strength started at the early stages in the development of concrete technology with the direct tension test and the flexural test. Several methods, more or less sophisticated, were later developed of which the splitting test has received special attention and has been standardized in many countries. Unhappily the tensile strength of concrete is found to be highly sensitive to the testing techniques and to the size and shape of the specimens used. This fact has prevented a deep understanding of the behaviour of concrete under tension and, therefore, has made the practical application of the tensile strength values obtained from tests highly unreliable.

In rock mechanics, the tensile strength is fundamentally important in that it determines the response of the material to dynamic forces, in drilling, blasting and breaking ground by means of wedge penetration devices, ploughs and rock rippers. The concept of tensile strength, in relation to the ability of a rock to resist dynamic attack or to support static loads, is little used as a design factor. It remains one of the least well defined because of the lack of an experimental technique that is both practical and reliable as well as rigorous from a mechanics point of view.

Most rocks are more or less brittle ; when unconfined, the test samples cannot yield plastically to relieve the stress concentrations that are produced at the localized points around the specimens, where these are gripped to be pulled apart by the testing machine. Consequently premature failure is generated from these points. Difficulties in ensuring truly axial loading also exist, so that the specimen is liable to be twisted or bent when gripped and pulled from either end.

Various direct and indirect testing methods have been developed, in attempts to resolve these difficulties and to determine the tensile strength of concrete. These can, in general, be grouped as follows :

(i) Bending tests : bending of prismatic and cylindrical specimens and bending of discs.

(ii) Hydraulic expansion tests.

(iii) Diametral compression of disc : Brazilian test and ring test.

(iv) Miscellaneous methods : diametral compression of cylinders, diametral compression of spheres, compression of square plates along a diameter and centrifugal tension.

The split cylinder Brazilian indirect tension test (Carneiro, 1947) has often been adopted and provides a simple means for obtaining the tensile strength of concrete as well as rocks. The popularity of this test stems from the fact that it is not only easy to perform, but it often uses the same cylindrical specimens and testing equipment that are used to determine unconfined compressive strength. Despite its popularity, however, it does not provide a precise measurement of the tensile strength. Past studies (Wright, 1955) have shown that the tensile strength as determined by the split cylinder tests may overestimate the true tensile strength of brittle materials by as much as 50%.

PROPOSED DIRECT TENSILE TEST

Direct tension applied to a specimen is theoretically the simplest method of determining the tensile strength. It is both practical and theoretically meaningful. The direct test is of more fundamental value because the stress field of an isotropic specimen is determined directly by the applied loading and the boundary conditions, irrespective of the material properties. Indirect tests have the inherent disadvantage that a stress strain relationship must be assumed in order to obtain usable results ; the usual assumption of linear elasticity, with equal moduli in compression and tension, is invalid for some concretes and many rocks. However there are major difficulties in gripping the specimens and applying a load parallel to the axis of the specimen.

The new proposed test specimen is a cylindrical tube (Fig. 1). The test sample is easily prepared, with two parallel flat ends and two inversed tubular coaxial borings. The external surface requires no particular preparation.

The proposed configuration converts the applied load on the specimen into a tension, so that the usual compressive test machine can be used. The cylindrical symmetry permits self alignment of loads parallel to the axis of the specimen. The test requires no special device for specimen gripping and compressive loads for example can be applied without any precaution. There will be no tendency to cause bending so that abnormal stress concentrations are avoided.

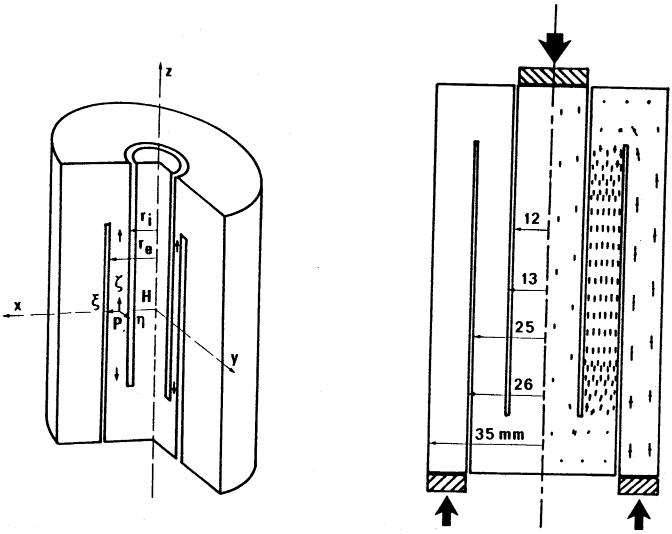

Fig. 1 - Geometry of the proposed tensile test specimen.

In particular, this test can be conducted in hostile environmental conditions : high temperature testing, long duration testing (creep or relaxation), immersed conditions, high confining pressure, under irradiation, or shock loading, and so on.

The main advantage of the proposed direct tensile test is evidenced by the uniformity of uniaxial tension stress throughout the test volume. Thanks to its cylindrical symmetry, there is no bending or torsional stresses, no stress concentrations arising from geometrical irregularities of the sample and no end restraint effects perturbing the stress field : most of observed failures occur in the central part of the specimen (Fig. 2).

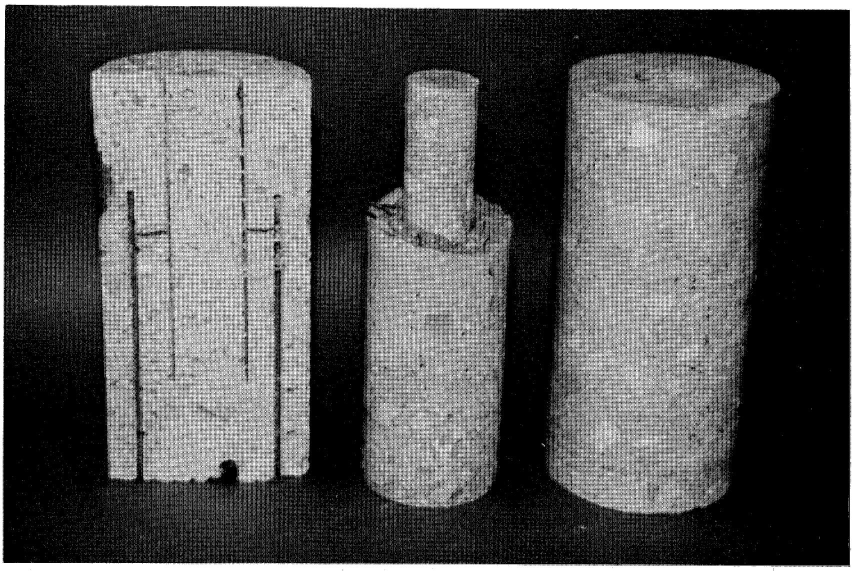

Fig. 2 - Tensile test specimen of concrete restored by gluing.

Several series of tests with optimized dimensions (r = 25 mm for external radius and mr = 13 mm for internal radius) have given an average uniaxial tensile strength $R_I = F/\pi r^2 (1 - m^2)$ as shown in Fig. 3.

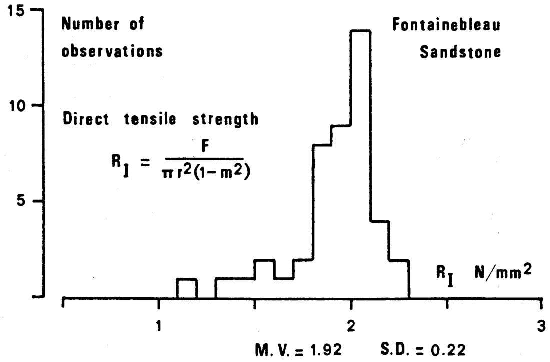

Fig. 3 - Histogram of tensile test observations on Fontainebleau sandstone.

DIRECT SHEAR STRENGTH

The shear resistance is of considerable concern for intense short-pulse blast, penetration of projectiles into concrete, seismic loading of nuclear containments or tall building structures.
Shear strength is often used to cover several different concepts such as (a) strength against pure shear, (b) shear stress required for failure without normal stress, (c) shear diagram on solid interface depending upon normal stress and (d) Mohr's stress envelope.

According to Everling (1964), shear strength $\tau = T/A$ can be defined as the breaking shearing stress applied to an imposed surface supporting no normal force, where T is the shearing force necessary to cause failure along a surface and A denotes the cross sectional area along which failure occurs. Shear strength of rock is often measured by torsion of a cylindrical specimen or a specimen with a neck or by a single shear test, double shear test and punch test. In these tests, tensile stresses are present. There are caused by bending and stress concentrations near the shearing edge. High shear stresses occur at the loading edges and hence stress is not uniform on the fracture surface. Then, the breaking force will be lower than that when stress distribution is uniform and permits fractures to develop freely.

Several methods are devised for measuring shear strength of rock : torsion test, single shear test (Bernaix, 1969), double shear test, punch test, shear loaded beam with starter notches according to mode II of fracture mechanics.

Concrete and rock materials are usually weaker in tension and comparatively stronger in shear, the cracking will often occur essentially in tension. It must be borne in mind that in such a case, the test was in fact an indirect tension test.

The main requirements of a Mode II test specimen must be : simple compact geometry, ease of preparation, simple loading system and stress conditions little affected by extremely small geometric alterations.

Attempts to realize mode II crack propagation on a laboratory scale usually fail because mode I growth takes over. On the other hand, traces of mode II growth are often detected at or after earthquake slipping. The following part of the present paper proposes a direct shear test that maximizes mode II conditions of crack propagation in concrete.

PROPOSED DIRECT SHEAR TEST

To avoid the dilatancy effect caused by the external tubular part, the specimen subjected to direct shearing, defined as mode II of fracture mechanics, is fabricated as shown in Fig. 4.

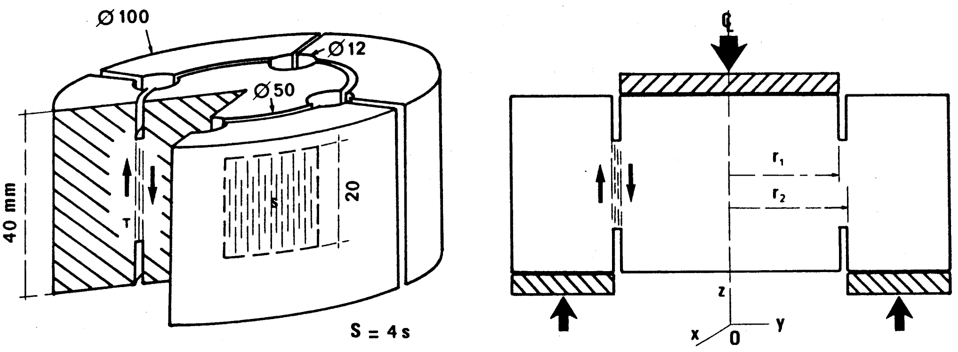

Fig. 4 - Geometry and optimized size of the proposed shear test specimen.

The axial load F is applied on the central cylinder of the specimen which is retained by the four concentric tubular parts. The notches define the sheared zone S = 4s.

The specimen geometry has been optimized by a numerical analysis of stress intensity factors in mixed modes problems by path independant intregrals J_I and J_{II} (Bui, 1982). A criterion for deciding whether the crack will grow in mode I by formation and extension of a kink or in mode II in the original crack direction, was established similarly as done by Melin (1986) by comparing the stress intensity factors $K_{I_{max}}$ for a small kink with $K_{II_{max}}$ for the main crack. If K_{I_c} and K_{II_c} denote the critical stress intensity factors for mode I and II respectively, mode II growth will be prefered to mode I if

$$\chi = \frac{K_{IImax}}{K_{Imax}} > \frac{K_{II_c}}{K_{I_c}} = \chi_c$$

Several series of tests have been performed on specimens of concrete and rock materials at different sizes to analyse the scale effect (Fig. 6). The nominal strength is given by F/4s.

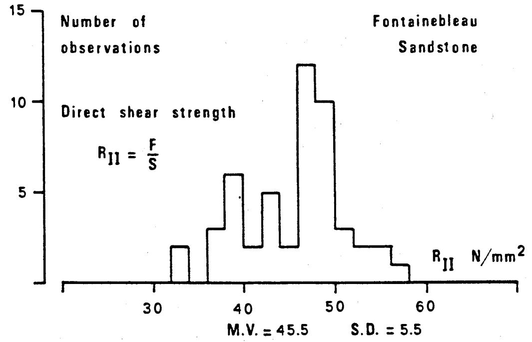

Fig. 5 - Histogram of direct shear test observations Fontainebleau sandstone.

DIRECT TORSION STRENGTH

Conventional techniques of determining shear strength of rock materials use indifferently tests which promote mode II or mode III of fracture mechanics (Lama & Vutukuri, 1978). However Protodyakonov (1969) has noted that rock fracture in a torsion test is not in fact due to shear but a tensile one and this must be borne in mind.

A tubular cylindrical specimen for direct torsion testing is proposed for the determination of mode III fracture strength of concrete and rock materials. It is a square cross section prism with a thin cut turned in its central part. It is assumed that, in spite of the low tensile strength of concrete and rock, fracture will occur from shearing stresses in mode III, since the screw-shaped surface of tensile fracture would be much larger than the thin round neck under torsion. When it is subjected to torsion T by holding its end in chucks, maximum mode III shear stress develops at the outermost fibre. The nominal mode III strength (Fig. 6) can be given by :

$$R_{III} = T / \pi r^3 (1 - m^3)$$

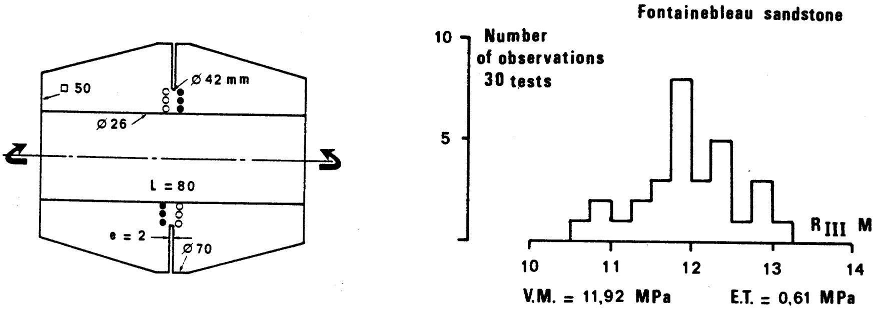

Fig. 6 - Histogram of direct torsion test observations on Fontainebleau sandstone.

CONCLUDING REMARKS

The unsuitableness of the usual testing techniques for the determination of tensile and shear strengths has suggested these devices for evaluating the direct tensile, direct shear and direct torsion strengths which correspond respectively to mode I, mode II and mode III fracture resistance of concrete and rocks. The three proposed testing arrangements simplify the loading equipment. They are practical and reliable. They also facilitates the testing procedure when concrete or rocks are subjected to severe and hostile environmental conditions. And finally they can both be used as routine tests.

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