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Standards for Fracture Toughness Testing of Rock and Manufactured Ceramics: What Can We Learn for Concrete?

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ABSTRACT: This paper presents a review of the American Society for Testing and Materials (ASTM) and the International Society for Rock Mechanics (ISRM) standards for determining the plane-strain fracture toughness of cemented carbides and rocks, respectively, with an eye toward applicability to concrete. The evolution of the chevron-notched test specimen used in these standards is briefly reviewed. A discussion of a particular chevron-notched configuration, the short rod test specimen, and associated test methods follows. The ASTM and ISRM standards are then described. The paper evaluates the potential for learning from, modifying, or adapting these standards for use on a standard fracture toughness test for concrete. The potential advantages and disadvantages of using the short rod geometry and testing methods on concrete are discussed, taking into account fracture response, shape, volume, preparation, precracking, symmetry, and subsize specimen effects. Preliminary research into the applicability of the short rod geometry and testing procedures on concrete is discussed.

KEYWORDS: concrete, fracture toughness testing, short rod specimen, linear elastic fracture mechanics (LEFM), nonlinear fracture mechanics, subsize specimen

Nomenclature

a	Crack length
a_c	Critical crack length beyond which crack propagates unstably
a_{min}	Crack length corresponding to F^*_m
a_0	Initial crack length, distance from load line to tip of chevron notch
A_F	Fracture area
B	Diameter of short rod specimen
CMOD	Crack mouth opening displacement
E	Modulus of elasticity
F^*	Normalized stress-intensity factor for short rod specimen
F^*_m	Minimum value of normalized stress-intensity factor
G_f	Fracture energy, critical energy release rate from size effect model
G_{Ic}	Energy required per unit area swept out by a quasistatic steady-state crack tip in a plane-strain field; critical energy release rate
H	"High" load on the unload cycle
K_I	Stress-intensity factor, Mode I
K_{Ic}	Critical stress-intensity factor, fracture toughness
K_{IcSR}	Plane-strain fracture toughness measured with the short rod method
K_Q	Apparent critical stress-intensity factor, fracture toughness
L	"Low" load on the reload cycle, defined as half corresponding "high" load
t	Notch width
p	Inelastic behavior correction factor
P	Applied prying force, load
P_c	Prying force corresponding to F^*_m
P_{max}	Maximum prying force, maximum load
R_{SR}	Specific work of fracture for short rod specimen
U_e	Elastic strain energy in specimen at zero applied load
w	Length of specimen
W^f_{SR}	Work of fracture for short rod
ΔW	Increment of irrecoverable work done to advance the crack front
Δx_0	Base of trapezoid created by two unloading cycles, measured at zero load
Δx	Top of trapezoid created by two unloading cycles, measured at average load between unload points
ν	Poisson's ratio

Introduction

A U.S. standard test method for measuring the fracture toughness of concrete, K_{Ic}, does not currently exist. However, there are standards for fracture toughness testing of other ceramics, manufactured and natural. Included here is a review of two such standards with an eye toward applicability to concrete: the ASTM Standard Test Method for Short Rod Fracture Toughness of Cemented Carbides (B 771-87) and the International Society for Rock Mechanics (ISRM) Suggested Methods for Determining the Fracture Toughness of Rock (ISRM 1988). This paper will address the question: Are there technologies embedded in these standards worth exploring in the context of toughness testing of concrete?

At the heart of both test standards is the fracture behavior of a chevron-notched test specimen. This behavior is briefly reviewed. A more particular discourse on a specific chevron-notched specimen, the short rod, is presented. How this particular specimen is used within the ASTM and ISRM standards is then discussed. An evaluation of the potential for learning from, modifying, or adapt-

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ing these standards for use on a standard toughness test for concrete follows. As a ceramic, concrete has its own unique material behavior. Currently perceived potential advantages and disadvantages of using the short rod geometry and testing methods on concrete are discussed, taking into account fracture response in the test specimen, the short rod specimen configuration, test method issues, and the potential for subsize specimens. Topics within the short rod specimen configuration include shape, volume, preparation, precracking, and symmetry. Test method issues deal with linear elastic fracture mechanics (LEFM) and nonlinear test conditions. Some fracture characteristics of concrete which differentiate it from other manufactured ceramics and rock are addressed. The important issue of scale effect as it pertains to specimen size is presented. The discussion culminates with preliminary research into the use of the short rod geometry and testing procedures on concrete.

Background

In the late 1970s ASTM formed task groups to study the feasibility of developing standards for fracture toughness testing of brittle nonmetallics, such as manufactured ceramics and rock. Substantial progress on standardized testing has been made with respect to some manufactured ceramics and rock. In 1987 ASTM published B 771. ISRM also fostered the development of a standard for rock in the mid-1980s, culminating in a published standard in 1988 (ISRM 1988). Common to both methods is the short rod test specimen geometry shown in Fig. 1.

History of the Chevron-Notched Specimen

The short rod was not the first chevron-notched fracture specimen. A detailed history of the evolution of the chevron-notched fracture specimen is found in Newman (1984) and is highlighted here. In 1965, Nakayama (1965) introduced a bend specimen with an unsymmetrical notch (Fig. 2*a*). Tattersall and Tappin (1966) introduced the chevron-notched bend bar (Fig. 2*b*). The benefits of these chevron-notched configurations include the following:

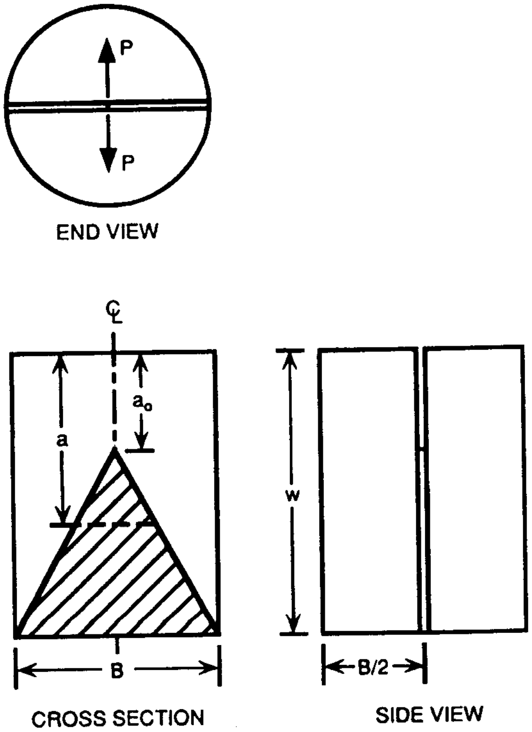

FIG. 1—*Short rod specimen geometry.*

1. The geometry obviates the need for precracking because application of load eventually initiates a natural crack at a known location, the apex of the chevron.
2. The notch enforces a known asymmetry (Fig. 2*a*) or symmetry (Fig. 2*b*).
3. The deep side grooves result in a higher condition of plane-strain across the crack front, and cause the crack to remain planar.

To determine fracture toughness, Nakayama (1965) and Tattersall and Tappin (1966) calculated work of fracture by measuring the area under the load-displacement curve. This method is similar to an earlier draft recommendation by the International Union of Testing and Research Laboratories for Materials and Structures (RILEM) for determining fracture energy of mortar and concrete (RILEM 1985).

Barker (1977) then introduced the short rod specimen (Fig. 1). The short rod specimen under LEFM conditions, however, requires measurement of only the maximum load.[2] The concept, as described by Pook (1972), is that:

> If the K_I against crack length characteristic is modified, by the introduction of suitably profiled side grooves, so that there is a minimum at $a/w \sim 0.5$, and the initial K_I is at least twice this minimum, it should be possible to omit the precracking stage, and obtain a reasonable estimate of K_{Ic} from the maximum load in a rising load test.

The chevron notch of the short rod specimen serves as these ". . . suitably profiled side grooves . . . ." This simple measurement and the resulting calculation are some of the most important potential advantages of a short rod based fracture toughness testing procedure.

Description of the Short Rod Test Under LEFM Conditions

The short rod test for K_{Ic} proceeds as follows. An increasing prying force is applied to the notched end. Due to the sharp point at the tip of the chevron, a crack initiates (pops in) at a load much less than the maximum load. As the applied load increases, the crack advances stably until the critical length, a_c. At this point

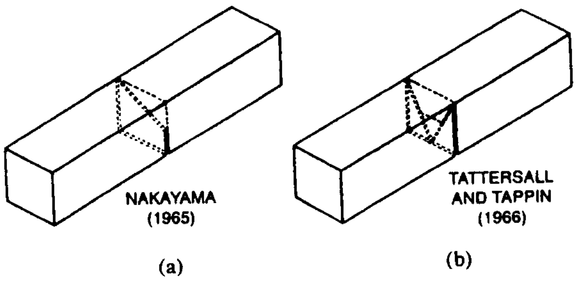

FIG. 2—*Early chevron-notched specimens. After Newman (1984).*

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[2] It will be shown later that for non-LEFM conditions, a full load displacement diagram must be recorded.

the crack propagates unstably under load control. The fracture toughness, K_{IcSR}, is then calculated by the formula

$$K_{IcSR} = \frac{F_m^* P_{max}}{B^{3/2}} \quad (1)$$

where P_{max} is the maximum prying force and F_m^* is the minimum value of the normalized stress intensity factor (a geometry specific parameter).

The underlying theory as envisioned by Pook (1972) and refined by Barker (1977) can best be discussed in conjunction with Fig. 3. The K_I versus a curves for several loads are shown as dashed lines. As the crack length, a, changes, F^* changes, and at a geometry specific point, F^* goes through a minimum value. Assuming that the pop-in load advanced the crack to point A, a load higher than P_1 must be applied in order to advance the crack. If the prying force is brought up to P_2, the crack will advance to B and stop because beyond B the resulting stress-intensity factor, K_I, is less than the critical value, K_{Ic}. At P_{max} the K_I versus a curve is just tangent to the K_{Ic} threshold line, and the crack is at D. If the crack advances slightly past D, K_I will always be greater than K_{Ic} and the crack will propagate unstably. At this point, F^* is at its minimum value, labeled F_m^*, and the corresponding crack length, a_{min}, is equivalent to the critical crack length, a_c. Therefore, as noted previously, the fracture toughness only depends on geometry specific constants and the maximum prying force.

Under conditions for which resistance is dependent on crack growth, a rising R-curve, which may occur in ceramics such as concrete, the method as described might not work. This point is illustrated in Fig. 4. In this case, the critical crack length, a_c, is not the same as a_{min}. Under the maximum prying force, the crack does not go unstable at the minimum K_I. Therefore, without knowing a_c and the corresponding value of K_I, one cannot accurately determine K_{IcSR} from Eq 1. However, Barker (1979) showed that compliance measurement may be used to correct for this behavior. Compliance is the ratio of crack mouth opening displacement (CMOD) to prying load. For the ASTM standard, $w/B = 1.45$, he showed that the compliance at the load corresponding to the minimum normalized stress-intensity factor, F_m^*, is approximately half of the initial compliance. Labeled P_c, this load is then substituted for P_{max} in Eq 1 to account for rising R-curve behavior. The ISRM standard, described later, uses this fact to overcome rising R-curve behavior in determining fracture toughness of rock.

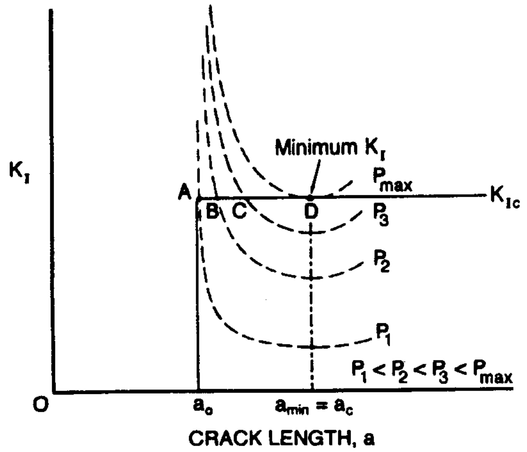

FIG. 3—*Fracture of brittle material using a chevron-notched specimen. After Newman (1984).*

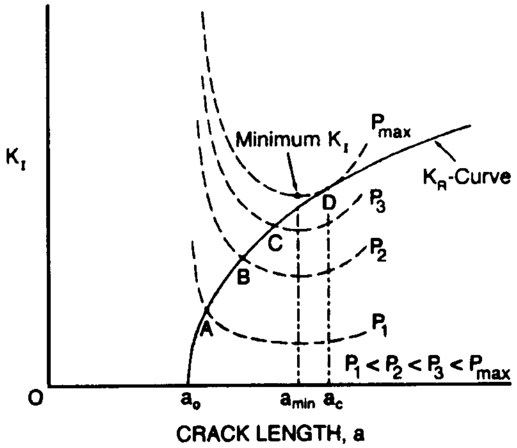

FIG. 4—*Fracture of rising R-curve material using a chevron-notched specimen. After Newman (1984).*

The K_I versus a curves shown in Figs. 3 and 4 came from experimental or analytical compliance calibrations. Experimental compliance calibrations involved testing many specimens in the lab to measure the compliance at various known crack lengths. An equation was then derived to fit the data points (Bubsey et al. 1982, Shannon et al. 1982, Barker 1983). Beech and Ingraffea (1982) used three-dimensional finite element analysis to obtain the compliance versus crack length data points. Other analytical compliance calibrations using the finite element method and the boundary element method were conducted to account for various geometries and Poisson's ratio effects (Raju and Newman 1984, Ingraffea et al. 1984). Newman (1984) has shown that the various compliance calibrations agree within about 3%.

Short Rod Test Under Non-LEFM Conditions

Barker developed the p-factor modification to the short rod test method for the situation in which LEFM conditions might not exist. This modification, explained in detail by Barker (1979) and outlined below, allows the use of a subsize specimen to determine K_{Ic}.

The method proceeds as follows. A sample load versus CMOD graph, Fig. 5, is obtained by testing the specimen in displacement control. At least two unload-reload cycles must be performed

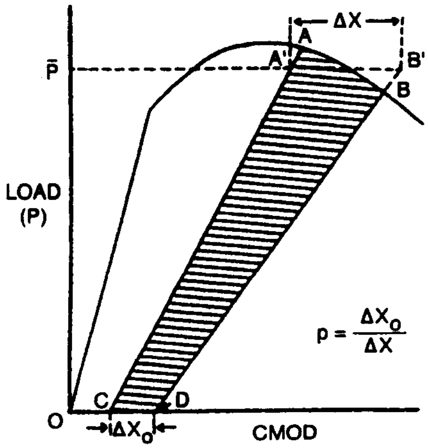

FIG. 5—*Schematic of inelastic specimen behavior. After Fig. 5 of Barker (1979), with permission from Kluwer Academic Publishers.*

during the test. Here the first of these cycles is represented by the line AC and the second by the line BD. Note that the linear elastic unloading does not return to the origin. This is due to non-negligible process zone effects. Barker (1979) showed that if the ratio of Δx_0 to Δx is labeled as p, then the fracture toughness, K_{IcSR}, can be determined from a subsize specimen using the following equation

$$K_{IcSR} = \left(\frac{1+p}{1-p}\right)^{1/2} K_Q \tag{2}$$

Here, K_Q is the apparent fracture toughness assuming LEFM and using Eq 1. The K_{IcSR} obtained using this method will be a material state property. Therefore, it may be applied to any structure of sufficient size to meet LEFM conditions even though the sample tested was too small to meet these conditions.

The p-factor method as presented by Barker accounts for inelastic process zone effects on the measured fracture toughness. Although Barker repeatedly refers to the "plastic zone" and "elastic-plastic" behavior, none of his assumptions in the derivation of the method preclude other damage mechanisms in the process zone. In fact, Barker (1979) indicates that:

> Similar results were obtained in a previous specimen size effect study of Indiana limestone rock, in which a microcracking process zone at the crack tip produces the same residual specimen mouth opening effect as the plastic crack-tip zone in metals.

Therefore, the p-factor method is valid for ceramics, rock and, presumably, concrete.

An important part of Barker's derivation is the assumption of a steady-state crack. This is defined as:

> . . . a crack which has quasistatically propagated sufficiently far in a single loading sequence such that a further quasistatic crack advance will produce no change in the configuration of the crack tip, including the surrounding crack-tip plastic zone (Barker 1979).

The "quasistatic" requirement avoids the realm of dynamic fracture mechanics. The crack tip must advance "sufficiently far" to eliminate any transient effects in the process zone due to crack initiation. The final part of this statement implies that the incremental work absorbed by the inelastic process zone is zero during the "steady state." The process zone does not grow; therefore, all work absorbed during crack propagation must be absorbed by other mechanisms.

The two mechanisms that account for the irrecoverable work done on the specimen are crack propagation and stored elastic strain energy. In an unload-reload cycle, the irrecoverable work, ΔW, that advances a steady-state crack of width b a distance Δa must be related to these mechanisms by (Barker 1979)

$$\Delta W = (bG_{Ic} + \partial U_e/\partial a)\Delta a \tag{3}$$

The term $(bG_{Ic})\Delta a$ is the energy consumed to propagate the crack by Δa. The term $(\partial U_e/\partial a)\Delta a$ is the elastic strain energy increment stored in the specimen. An important assumption in the derivation of the p-factor method is that the second term is insignificant with respect to the first term.

Barker (1981) continued to explore the advantages of the short rod test method and discovered that the p-factor method will account for macroscopic residual stresses in a specimen. Few other fracture toughness test methods account for macroscopic residual stresses, even though the residual stresses may affect the measured fracture toughness. In a specimen under LEFM conditions, an unload cycle will return to the origin of a load versus CMOD graph. If there are macroscopic residual stresses present in the specimen (Fig. 6), the unload cycle will not return to the origin. The load versus CMOD graph will appear as in Fig. 5 even under LEFM conditions. Barker showed that the p-factor method corrects for these macroscopic residual stresses. A positive p-factor corresponds to the situation in Fig. 6. A negative p-factor ($\Delta x_0 < 0$) corresponds to residual tension along the cracked faces. Barker further showed that for a non-LEFM specimen with macroscopic residual stresses, the p-factor corrects for both conditions simultaneously.

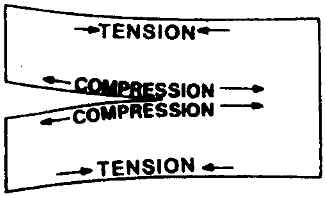

FIG. 6—*Illustration of macroscopic residual stresses which may affect the measured fracture toughness. After Barker (1981).*

ASTM B 771—Standard Test Method for Short Rod Fracture Toughness of Cemented Carbides

In 1987 ASTM first published B 771. The standard evolved based primarily on research done by Barker (1977, 1978, 1979, 1981, 1983; Barker and Baratta, 1980). Specifically, Barker (1981) and Tingle et al. (1984) each published results of studies of various types of tungsten carbides using the p-factor method. The test follows the standard procedure outlined by Barker (1979) using the p-factor approach to determine K_{IcSR}. The dimensions of the short rod specimen were set at B = 12.7 mm, w = 19.05 mm, and a_0 = 6.74 mm. For typical cemented carbides, this size ensures a LEFM condition. Therefore, the p-factor in this case is used to account for residual stresses in the specimen.

The standard clarifies how to find the compliance of the unload-reload cycles. As the applied load decreases to 10% of the maximum, test results show that the slopes of the unload-reload lines do not always remain linear (Fig. 7). Therefore, the standard specifies that the slope be determined from the "high" load, points "H"

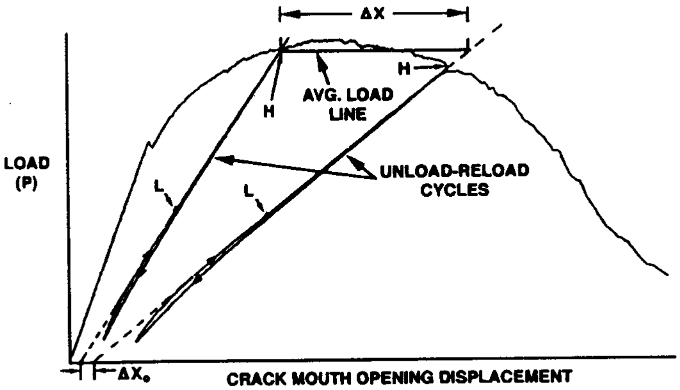

FIG. 7—*Sample load-displacement test record. After ASTM (1987).*

in the figure, where the CMOD began to decrease during unloading, and from the "low" load, points "L," which is half the "high" load measured during reloading. A line is drawn through the two points down to the CMOD axis. This method thus corrects for any nonlinear behavior in the lower half of the unloading-reloading cycle.

The standard also comments on imperfections in the crack plane near the critical crack length. According to ASTM, the test is valid only if there are no visible imperfections in the region near the critical crack length, a_c. Imperfections include voids, surface irregularities, and foreign matter. Cemented carbides, which may include tungsten, titanium, tantalum, or molybdenum, typically comprise a fine microstructure of carbides held together by a binder. The average grain size in this microstructure is on the order of 1 to 10 μm (Schwarzkopf and Kieffer 1960). Therefore, the ASTM standard dimensions result in an average ratio of grain size to specimen diameter of 4×10^{-4}. Visible imperfections, on the order of 0.1 to 1 mm, in a pure cemented carbide therefore represent anomalies over 100 times the average grain size. The test becomes invalid, according to ASTM, in this case because the peak load, P_{max}, may be affected.

The short rod method outlined above has been used successfully on other manufactured ceramics as well. Lewis (1990) points out that the short rod is rapidly becoming one of the most popular fracture toughness testing methods in the ceramics community. Wolf et al. (1993) used the short rod method to determine the fracture toughness of alumina-glass dental composites. Moody et al. (1995) used the same method to determine the fracture toughness of borosilicate glasses. During development of the ASTM standard, Shannon and Munz (1984) performed short rod tests on four sizes of short rod and several sizes of short bar specimens of sintered aluminum oxide (Al_2O_3). Their results showed a size effect in the measured K_{Ic}. They attributed this effect to rising R-curve behavior. They noted that rising R-curve behavior of pure alumina had already been established (Hübner and Jillek 1977). Although the standard does not explicitly address this issue, the p-factor approach inherently provides some correction for the rising R-curve behavior. If the ASTM standard required use of the load corresponding to a compliance half that of the initial compliance, then the calculated fracture toughness would be more accurate. The ISRM standard, however, does incorporate this step explicitly.

ISRM Standard for Fracture Toughness Testing of Rock

Soon after ASTM first published B 771, ISRM (1988) was published. The ISRM standard combines two test geometries: the chevron-notched bend specimen (Fig. 8) and the short rod. The short rod specimens are created from the halves of a tested chevron-notched bend specimen. This method allows the tester to obtain three values of K_{Ic} from a single core sample.

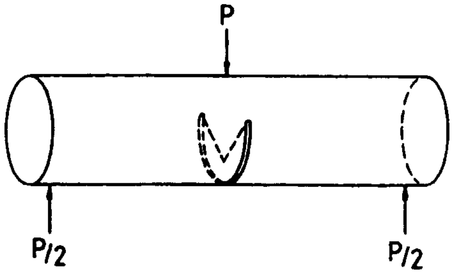

FIG. 8—*Schematic drawing of chevron-notched round bar in bending. After Atkinson and Meredith (1987).*

According to Atkinson and Meredith (1987):

> Observations of the fracture process in a number of brittle rocks have shown that such microcracking can take place at a significant distance from the macrocrack tip compared with specimen dimensions normally used.

The existence of a microcracking process zone invalidates specimen size requirements based on a plastic process zone (Ingraffea and Gerstle 1984) and makes fracture toughness testing methods that require measuring crack length very difficult to use. Two nonlinear testing techniques that have been applied to rocks are a J-integral based approach applied by Wilkening (1978) and Weisinger et al. (1980), and the short rod method with the inelastic correction factor (Barker 1979; Ouchterlony 1986a). Wang and Xian (1992) point out that the p-factor takes into account the severity of grain interlocking and the effect of crack tip fracture process zone in rock.

The ISRM standard uses the p-factor to correct for nonlinear effects in both the chevron bend specimen and the short rod specimen. The method is consistent with Barker's derivation as described previously. The standard also uses the procedure outlined by Barker to account for rising R-curve behavior. One additional check included in the ISRM standard that is not part of ASTM B 771 is calculation of the work of fracture, W^f_{SR}. If the load versus CMOD graph is continued until the specimen has almost no residual strength, the work of fracture is the area under the curve. Mathematically, this is represented by

$$W^f_{SR} = \int_0^\infty Pd(\text{CMOD}) \tag{4}$$

The specific work of fracture is the work of fracture, calculated with Eq 4, normalized by the fracture area, A_F

$$\overline{R}_{SR} = W^f_{SR}/A_F \tag{5}$$

The specific work of fracture should correlate closely to the critical energy release rate, G_{Ic}, which is related to the fracture toughness by the following relationship

$$G_{IcSR} = (1 - \nu^2)(K_{IcSR})^2/E \tag{6}$$

This simple check provides more insight to the validity of the test results.

The pioneer for the standard test method for rock was Ouchterlony (1980, 1983, 1986a, 1986b). He and other key researchers built a library of literature to support the standard method used today. The standard itself lists 71 references to support its development. During development of the ISRM standard, researchers identified a size effect in rock when determining values of K_{Ic} measured by various methods, including the short rod (Ingraffea et al. 1984). Just as in manufactured ceramics, this behavior is likely due to the rising R-curve behavior of most rock types tested in laboratory scale specimens. Wang and Xian (1992) showed that, by using the p-factor correction on chevron notched bend specimen results, a K_{Ic} with reduced size effect could be obtained for Chongqing limestone. The ISRM standard cites works by Ouchterlony and Sun (1983) and Yi (1987) which show that:

> . . . corrected fracture toughness values may be reasonably independent of the specimen size (ISRM 1988).

Short Rod Based Testing Procedures: What Can Be Applied To Concrete?

The survey of existing practices outlined previously has shown that there have emerged three distinct methods of testing applicable to the short rod geometry. Method 1, referred to as Level I in the ISRM standard, is based on the assumption of LEFM conditions. Level I uses Eq 1 and requires measurement of only P_{max}. Method 2, referred to as Level II in the ISRM standard and used in both standards, does not assume LEFM conditions. Level II uses Eq 2 and requires a load versus CMOD graph with unload-reload cycles. Method 3, referred to as work of fracture in the ISRM standard, uses Eqs 4 to 6 and is a check on the Level II results. Note that the work of fracture was also used in a draft test method recommendation for concrete (RILEM 1985).

Having presented the evolution of the short rod geometry and several test procedures using the geometry, the potential advantages and disadvantages of using this geometry and these procedures as a standard test for measuring the fracture toughness of concrete are discussed. Key issues are fracture response in the test specimen, the short rod specimen configuration, test methods, and subsize specimens.

Fracture Response in the Test Specimen

Although the process zone damage mechanism for concrete, microcracking, is the same as that of other manufactured ceramics and rock, the fracture response of concrete may vary widely. Changes in cement content, aggregate size, aggregate strength, or many other material characteristics will alter the fracture response. Fracture response refers to the planarity of the crack and the degree of nonlinearity during fracture. This concept must be understood before the potential advantages or disadvantages of the short rod specimen and associated test methods can be discussed.

Consider for example two Level II tests performed on short rod specimens of granite and aluminum. Takahashi et al. (1986) performed such tests on granite with an average grain size of 1.3 mm using short rod specimens with a 51 mm diameter. The grain size to specimen diameter is about 0.025. They obtained an average p-factor of 0.26 for the samples. Barker (1979) performed Level II tests on aluminum using short rod specimens with a 12.7 mm diameter. Assuming that the typical grain size is 50 μm, the grain size to specimen diameter ratio is on the order of 0.004. Barker obtained an average p-factor of 0.21, a comparable value. The grain size to specimen diameter ratios, however, differ by almost an order of magnitude. This simple example shows how very different materials may exhibit very similar fracture behavior.

Concrete behavior is very sensitive to the constituent materials and their proportions. For example, Gutiérrez and Cánovas (1996) have shown that selection of specific aggregates and cement types are critical for obtaining high-performance concretes. A visual example of different fracture behaviors is provided. Figure 9*a* shows a tortuous, interaggregate fracture behavior; Fig. 9*b* shows a flat, transaggregate fracture behavior. Both short rod specimens have a diameter of 150 mm and a maximum aggregate size of approximately 9 mm. The material in Fig. 9*a* had a compressive strength of approximately 45 MPa; that in Fig. 9*b* had a compressive strength of approximately 70 MPa. The failure surfaces clearly indicate different cracking mechanisms were at work.

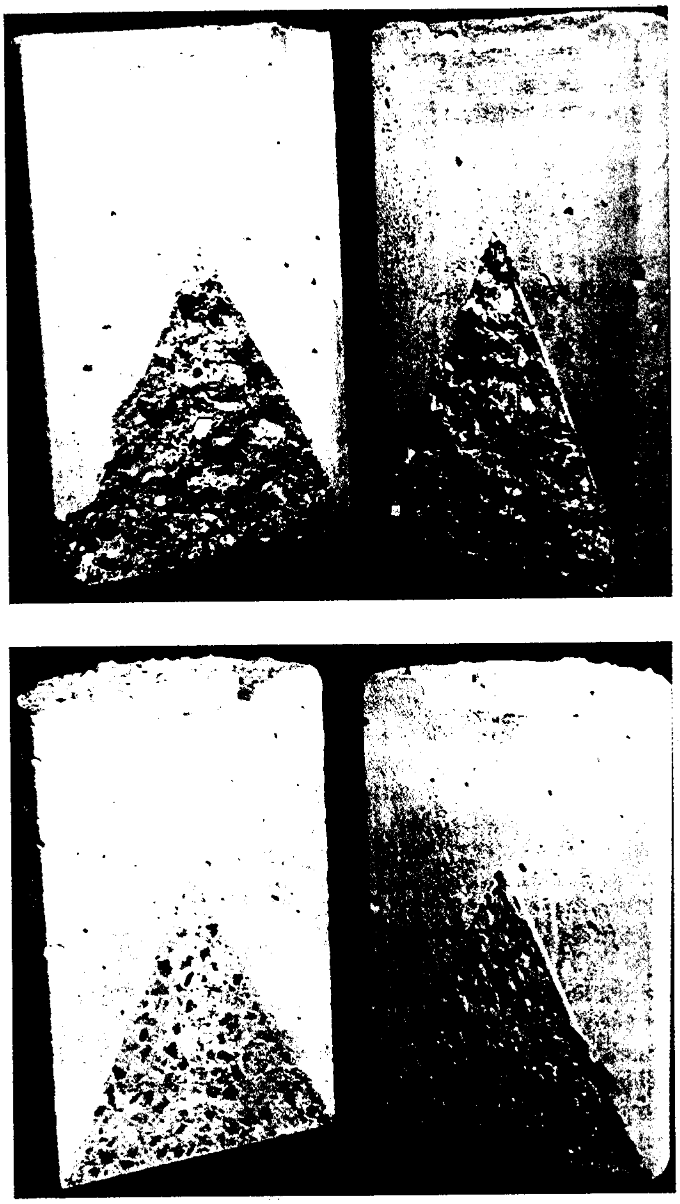
(*b*) *70 MPa compressive strength*

FIG. 9—*Crack surfaces of concrete short rod specimens. Maximum aggregate size is 9 mm.*

Similar changes in fracture have been noted by Mindess et al. (1994). They used the chevron-notched bend specimen (Fig. 8) and the ISRM method I (ISRM 1988) to determine the fracture toughness of microconcretes and paste/rock interfaces. In the microconcretes, they observed a flatter, more transaggregate fracture behavior for lower water/cement mixtures versus higher water/cement ratios. Therefore, one can conclude that maximum aggregate size alone cannot be used as a definitive determinate of fracture behavior in concrete.

The ISRM standard recommends using a short rod specimen with diameter at least ten times the largest grain size. This rule of thumb comes from results of many testing programs on rock. In light of the previous discussion on fracture behavior, it is important to note that this rule of thumb may not apply to all strengths of concrete. One might conjecture that as concrete mixtures go from low to high strength, the maximum aggregate size becomes less important and other material characteristics become more dominant.

Some preliminary work has been done to investigate the applicability of the short rod geometry and associated methods to concrete

TABLE 1—*Summary of results of fracture toughness testing on concrete by Catalano (1983).*

Series	Compressive Strength, (MPa)	K_{QSR} Mean ($MPa\sqrt{m}$)—COV	$K_{QSEN(B)}$ ($MPa\sqrt{m}$)	Maximum Aggregate Size, (mm)
A	60.7	1.18—5.3%	~1.2	<6 mm (mortar)
B	45.5	1.24—8.7%	~1.5	9 mm
C	43.4	1.02—13%	~1.6	19 mm

(Catalano 1983). Catalano conducted Level I testing on three mixtures of concrete with compressive strengths from 43 to 61 MPa (6.3 to 8.8 ksi) and with three different maximum aggregate sizes. He compared the K_Q measured from the short rod specimens with the K_Q determined by tests on chevron-notched, single-edge-notched-bend, SEN(B), specimens using the same mixtures. Catalano showed that by increasing the aggregate size, the behavior of the concrete changed such that short rod results diverged from beam results (Table 1). He attributed this observation to the increased inhomogeneity along the crack front at a_c. However, in light of the earlier discussion of material behavior, one cannot generalize these particular results to every mixture of concrete.

Short Rod Specimen Configuration

The short rod specimen configuration (Fig. 1) has been shown to have several advantages for use on manufactured ceramics and rock. Some or all of these advantages may apply to concrete as well.

- Shape. The short rod specimen can be created from a core sample readily obtained from an existing structure. For quality control purposes, concrete cylinders are already made on a routine basis in the United States for compression tests (ASTM 1996a) and split cylinder tests (ASTM 1996b). Therefore, forms of the correct shape are readily available across the country.
- Volume. For a comparable fracture area, the short rod requires approximately ten times less material than a SEN(B) specimen which is the geometry proposed by RILEM (1985, 1990a, 1990b) for determining the fracture toughness of concrete. The more compact geometry of the short rod versus a bend beam makes it easier to handle in the lab and probably makes the short rod easier to position for testing.
- Preparation. It is more difficult to cut the chevron-notch into a concrete cylinder than to cut a straight-through-notch in a rectangular beam. However, when testing is not being performed on existing structures, the chevron-notch may be cast into cylinders (Catalano 1983). The wall effect noticed in SEN(B) specimens with a cast in notch is not, however, likely to be an issue for the short rod. Chevron-notched bend specimens (Fig. 8) were chosen by Alexander and Mindess (1995) for measuring the fracture toughness of paste/rock interfaces because of the simple specimen preparation of cored samples.
- Precracking. A distinct advantage of any chevron-notched specimen is that it automatically generates a natural crack at relatively low loads without requiring fatigue precracking. A natural crack therefore exists at a_c, and the wall effect is avoided at the critical load.
- Symmetry. The notch of the short rod geometry helps enforce two symmetries: planarity and uniformity. The notch helps keep the crack in a single plane along the groove of the specimen: planarity. It also helps keep the crack front symmetric across the diameter of the specimen: uniformity. All test methods that depend on calibration to determine K_{Ic} or G_{Ic} assume a planar and symmetric crack front. Any actual variation in these two assumptions will inevitably lead to error and large scatter in the results.

Test Method Issues

Several aspects of the three test methods from the ASTM and ISRM standards may be advantageous for use on concrete.

- Level I Testing. Under LEFM conditions, Level I testing may be conducted in an open-loop (load control) machine. Testing non-chevron-notched SEN(B) specimens requires a closed-loop servo control (displacement control) machine even under LEFM conditions. This requirement exists because after the pop-in load, the bend specimen typically requires an ever decreasing load for stable crack propagation.
- Level II Testing. Physical setup of the short rod specimen for a Level II fracture toughness test may be more or less difficult than for other proposed fracture toughness tests for concrete. If the short rod is tested by wedge splitting, the setup is comparable to the splitting test as recommended by Linsbauer and Tschegg (1986) and Brühwiler and Wittman (1990). Since the test methods for the short rod use a different loading technique than flexure tests like those recommended by RILEM (1985, 1990a, 1990b), one can only speculate which will be more difficult to set up. Typically, compression tests, like wedge splitting of a short rod, require fewer fixtures and less preparation time than flexure tests. However, no real conclusion can be made until all of the methods are attempted and compared.

As discussed previously, the short rod geometry with Level II testing has been shown to account for residual stresses in some materials. This may or may not be of concern in concrete fracture toughness testing on any specimen. Further investigation is required to determine if Level II testing on concrete would account for any macroscopic residual stresses.

Subsize Specimens

Under non-LEFM conditions, concrete can exhibit a "specimen size effect." For the same concrete, two different sized specimens tested by the same method under non-LEFM conditions will likely produce two different measurements of fracture toughness. Results published by Hillerborg (1985) clearly show this effect. Hillerborg calculated the fracture energy, G_f, using the first draft test recommendation from RILEM (1985). Assuming that larger test specimens would eventually lead to a constant G_f, the size of specimen required for LEFM conditions may be cost prohibitive for many mixtures of concrete. A later recommendation by RILEM (1990b) uses results from at least three different specimen sizes to extrapolate to a size independent G_f. The same could be done with short rod specimens and Level I and/or Level II testing.

Some numerical simulations have been done by Bittencourt (1993) to investigate the potential of using a short rod specimen with Level II testing to obtain a size independent K_{IcSR}. Bittencourt developed fully three-dimensional analysis capabilities for cementitious materials using the fictitious cohesive crack model with unload-reload capability. He predicted specimen size effect behavior. He simulated Level II testing on five different diameters of short rod specimens. Using the same constitutive model for the process zone of concrete, he found that the inelastic correction factor, p, reduced as he scaled up the short rod dimensions. In calculating the fracture toughness, Bittencourt made no a priori assumption about the elastic strain energy increment stored in the specimen, $(\partial U_e/\partial a)\Delta a$. Results of his simulations indicate that $\partial U_e/\partial a$ can be negligible for specimens with a diameter on the order of 125 mm or larger. This conclusion validates the assumption made by Barker (1979). Bittencourt did not, however, perform any experiments on short rod specimens to compare to his simulations.

Conclusion

Although a U.S. standard for measuring the fracture toughness of concrete, K_{Ic}, does not currently exist, the fracture behavior of concrete suggests that a valid K_{Ic} might be obtainable from Level I or Level II testing on concrete using the short rod geometry *at some scale*. Review of the development of the short rod geometry and test methods does not produce any assumption that precludes application to concrete. The review does, however, suggest many possible advantages, and a few disadvantages.

Potential advantages and disadvantages of using the short rod geometry and test methods contained in the cited ASTM and ISRM standards on concrete have been addressed in the areas of fracture response in the test specimen, short rod specimen configuration, test method issues and potential for subsize specimens. The short rod specimen configuration presents potential advantages in terms of shape, volume, preparation, precracking, and symmetry. Level I testing, when LEFM conditions are present, requires measurement of only the maximum load. Under non-LEFM conditions (that is, subsize specimens), Level II testing can be used to obtain K_{Ic}. The results of some Level I tests on concrete short rod specimens (Catalano 1983) as well as the results of simulations of Level II tests performed on concrete short rod specimens (Bittencourt 1993), indicate that a valid K_{Ic} might be obtainable from subsize concrete short rod specimens with a diameter of 150 mm and compressive strength of 20 MPa (3 ksi).

Thanks to a grant from the National Science Foundation (NSF), collaborative research in three countries is now being conducted to determine if a valid K_{Ic} may be obtained from Level I or Level II testing on concrete using the short rod geometry. The research is being focused by a subcommittee of the joint American Concrete Institute (ACI)—Society of Experimental Mechanics (SEM) Task Group on Test Standards for Measurement of Fracture Properties of Concrete. This subcommittee is investigating the short rod and other cylindrical specimen geometries for fracture toughness testing of concrete.

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