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USE OF CHEVRON-NOTCHED CYLINDRICAL SPECIMENS FOR PASTE/ROCK INTERFACE EXPERIMENTS

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ABSTRACT

The paper discusses the applicability of the ISRM fracture beam specimen to the testing of interfaces between paste and rock. The method is suitable for interface tests in which rough fractured rock surfaces or prepared rock surfaces are required. Some typical results are presented and discussed in terms of different failure modes. A formula for equivalent elastic modulus of a composite beam is also introduced.

Introduction

Paste/rock interface experiments have been carried out for several decades (1-5). The interface bond depends to a limited degree on chemical interactions (5), but the inherent macro- and micro-texture of rock surfaces probably have a more important influence on mechanical properties of the interface (6). However, in all cases reviewed by the authors, tests have been done using rock surfaces prepared by sawing, grinding or polishing. No tests have been reported in which fractured rock surfaces were used, despite the fact that such surfaces are typical of crushed concrete aggregates.

Most of the tests reviewed have measured only a single parameter, generally the nominal bond strength calculated from linear elastic theory. Since interface problems involve crack growth and debonding phenomena, it would seem more useful to conduct fracture tests in which both toughness and fracture energy are measured. These two parameters are both important in the fracture process, the former governing crack initiation, and the latter reflecting nonlinear effects.

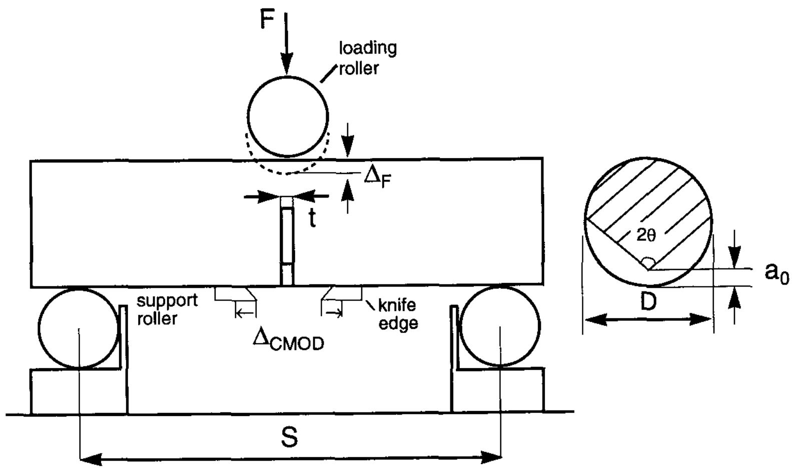
Interface toughness tests have been carried out for ceramic-metal interfaces by Mecholsky and Barker (7), using a chevron-notched double cantilever beam specimen. They maintain that the advantages of fracture tests over bond strength tests are better reproducibility and the ability to measure the energy required for unit crack advance, G_C.

In order to address the above issues, a cylindrical bend specimen based on the ISRM Method 1 (8) has been selected for paste/rock interface tests. One major advantage of the ISRM rock specimen is that it can be obtained by coring, rather than laborious cutting of a prismatic specimen. This method produces "naturally" fractured rock surfaces against which paste can be cast to produce an interface for testing (9). Subsequently, the rock surfaces can be ground or polished to remove the effects of macro-texture and re-tested. The purpose of this paper is to discuss the applicability of the ISRM specimen to interface experiments in cement-based materials.

Experimental Aspects

Figure 1 gives details for the ISRM Method 1 test on chevron-notched cylindrical specimens which in our tests are typically about 42 mm in diameter. We use loading-unloading cycles in order to propagate the crack stably through the notched section and obtain the full load-deflection envelope curve. Figure 2 shows a typical test record for a paste specimen. (It should be noted that Figure 2 can be used to generate an R-curve, assuming a suitable compliance calibration is available. However, this was not done in the present work.)

The ISRM test has an expression for fracture toughness K_{CB} which is based on compliance calibrations done by Ouchterlony (10,11) using results from tests on chevron-notched cylinders of uniform material. The expression for K_{CB} is:



D = diameter of cylindrical specimen
S = support span, 3.33D
2θ = chevron angle, 90°
t = notch width
a_o = chevron tip distance from bottom fiber
F = load on specimen
Δ_F = load point displacement (LPD)

FIG. 1
Chevron bend specimen for ISRM Method 1 (8).

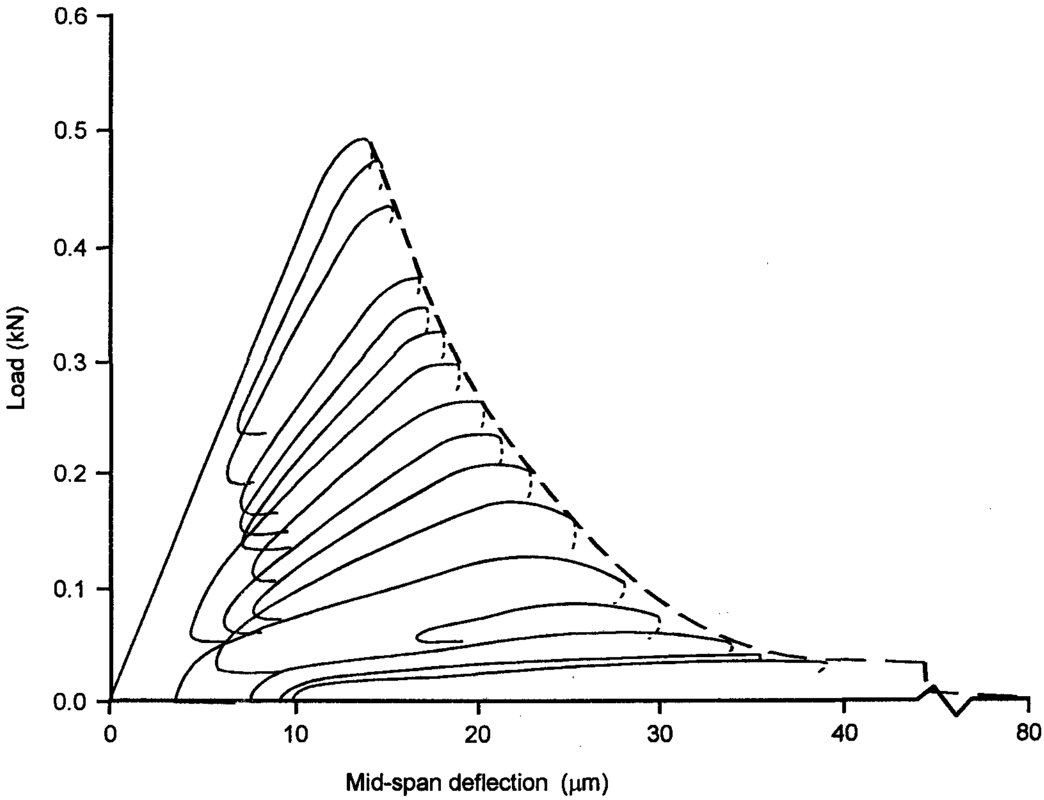


FIG. 2
Typical load-unload test record for a paste beam. (Full unloading curve not shown for clarity.)

$$K_{CB} = A_{min}\, F_{max} / D^{1.5} \tag{1}$$

where

$$A_{min} = [1.835 + 7.15\, a_o/D + 9.85\, (a_o/D)^2]\, S/D \tag{2}$$

F_{max} is the failure load, and D is the diameter.

For interface tests, the two halves of the beam are of different materials with different stiffnesses. This causes a distortion of beam deformations such that axi-symmetrical deflections about mid-span no longer occur. Nevertheless, the compliance (in terms of load point deflection) of each half of the beam is the same, and the composite beam's compliance can be matched by a uniform material with some value of E intermediate between the values for the beam halves (see Figure 3 and the Appendix). Applying the K_{CB} formula from Ouchterlony to interface tests therefore yields pseudo fracture toughness values, i.e. these values represent a situation in which the interface modifies the stress/strain distribution which would apply in a specimen of uniform material.

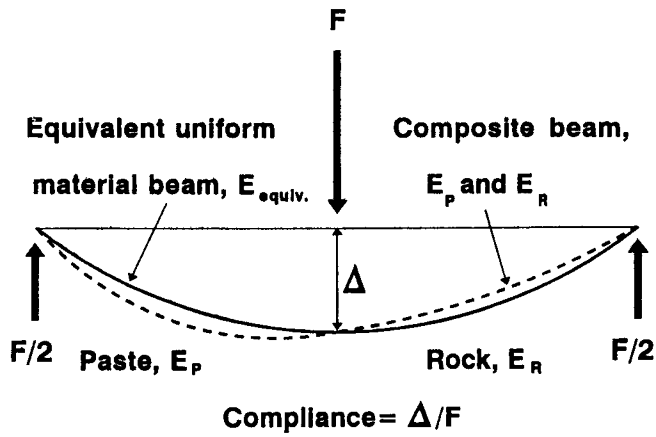


FIG. 3
Schematic of deflected shapes of an interface specimen and a uniform material specimen.

The use of the formula implies a uniform material with matching compliance behaviour. K_{CB} values can be converted to values of G_C, the critical strain energy release rate, using the LEFM expression. The elastic modulus value in this case must represent the composite beam, and is found from the slope of the initial straight line portion of the load-deflection record by applying the ISRM expression for E given in (8). The slope of this line will, to some degree, depend on the interface itself, particularly at early ages, and the measured E value may not reflect an ideal composite material. Assuming an ideal composite material, however, the G_C values will represent the toughness of the interface in terms of the work per unit area for a crack to separate the bonded materials.

The ISRM method permits the calculation of the specific work of fracture, R_{CB}, from the total work of fracture taken as the area under the load-displacement curve divided by the unnotched projected ligament area A (see Figure 1). This parameter is analogous to G_C and the two values should be equal for ideal linear elastic brittle materials. R_{CB} is a measure of the work per unit area of crack advancement.

The Appendix gives a formula for calculating the equivalent E for a composite beam, assuming ideal composite behaviour and knowledge of E values of the two constituent materials.

Table 1 shows measured K_{CB} values and R_{CB} values from ISRM tests on uniform material and composite material beams, G_C values calculated from the K_{CB} values and measured effective E values, and calculated equivalent E values for the composite specimens. In the main, G_C and R_{CB} values accord reasonably well, indicating materials that do not deviate excessively from LEFM assumptions. An exception is the andesite/OPC specimen, which might be explained in terms of the high interfacial bond strength and toughness of this composite, favouring additional energy-absorbing microcracking in the vicinity of the interface. Comparing calculated E_{equiv} values with measured E values shows that equivalent E can be predicted reasonably.

TABLE 1. Values from Fracture Tests (28 d)

		Measured			Calculated	
		E (GPa)	K_{CB} ($MN/m^{1.5}$)	R_{CB} (J/m^2)	G_C (J/m^2)	E_{equiv} (GPa)
Paste (w/c=0.3)	OPC	24.1	0.54	14.9	12.1	-
	OPC+SF	24.4	0.50	9.1	10.2	-
Rock	andesite	99.7	3.49	147.1	122.2	-
	dolomite	112.6	2.23	59.9	44.2	-
Rock/paste interface	andesite/OPC	45.6	0.80	24.6	14.0	38.8
	andesite/OPC+SF	38.2	0.71	14.5	13.2	39.2
	dolomite/OPC	46.8	0.57	7.5	6.9	39.7
	dolomite/OPC+SF	41.7	0.64	9.9(65d)	9.9	40.1

OPC - Ordinary Portland Cement; SF - silica fume at 15% replacement

In Mecholsky and Barker's tests (7), cracks either followed the interfacial plane, or on occasion deviated into the ceramic phase. Their results showed that the measured bond G_C could

- be equal to the value for the ceramic itself, or
- be less than the ceramic value, indicating a weaker bond, or
- be greater than that of the ceramic for failure within the ceramic phase.

Their tests were performed on interfaces which were smooth and planar. The authors point out that in the case of cracking outside of the bond plane, the test is no longer a valid test of interface toughness; all that can be said is that the interface toughness is greater than the value measured in the test.

In the case of ISRM interface tests that we have conducted:

- the tests were performed on rough fractured rock surfaces, which precludes the definition of a smooth interfacial plane 'per se'; in fact, surface roughness, a vital factor in aggregate bonding in real concrete, was probably the most important single factor in our tests
- cracks, on occasion, also deviated from the interfacial plane and penetrated the paste phase
- it was possible to measure toughness and work of fracture values greater than those of the paste phase (see Table 1).

One reason why interface values can exceed paste values is due to rock surface roughness which forces the crack in the interface specimens to follow a considerably more tortuous and microcracked path than is the case in a pure paste beam. Another reason is that different rock surfaces will develop different qualities of bond with paste, and it is conceivable that the interface bond in low w/c systems could be as tough as, or tougher than, the paste phase.

Conclusions

1) The ISRM bend specimen can be applied to testing the fracture properties of rocks, pastes, and rock/paste interfaces. It has the advantages of simple specimen preparation and the production of "naturally" fractured rough rock surfaces against which to cast paste.

2) The ISRM fracture formulae can be used to calculate toughness and fracture energies for constituent materials and interfaces, since the test arrangement produces equal bending compliances in each half of the test beam.

3) Under certain conditions, interfacial tests produce cracks which deviate from the interfacial plane and penetrate the paste phase. In this case, interfacial fracture toughness must be some value greater than the measured value.

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Appendix: Calculation of Equivalent Composite Beam E

The compliance formula from the ISRM method used to calculate the elastic modulus is (8):

$$g_o = \frac{ED}{S_{i.t.}} \quad (A.1)$$

where g_o = initial compliance (non-dimensional), E = elastic modulus, D = diameter, $S_{i.t.}$ = slope of initial straight line of the load-deflection curve. Therefore,

$$\frac{1}{S_{i.t.}} = \frac{g_o}{ED} \quad (A.2)$$

The equivalent compliance of a two-material composite beam can be found by considering the beam to be comprised of two halves, each half being a cantilever as shown in Figure 4. Assuming the slopes of the two cantilevers remain at zero at their junction at the centre, and applying the system of forces shown in Figure 4, the equivalent compliance of the composite beam is given by

$$\frac{1}{2}\left(\Delta_p + \Delta_R\right)/F \quad (A.3)$$

where the symbols are defined in Figure 4.

This can be written as,

$$\frac{1}{2}\left(\frac{\Delta_p}{F} + \frac{\Delta_R}{F}\right) \quad (A.4)$$

Δ/F is the inverse of the slope of the initial straight line of the load-deflection curve, i.e. $1/S_{i.t.}$

Therefore we can write,

$$\text{Equivalent compliance} = \frac{1}{2}\left[\frac{1}{S_{i.t_P}} + \frac{1}{S_{i.t_R}}\right] = \frac{1}{2}\frac{g_o}{D}\left[\frac{1}{E_P} + \frac{1}{E_R}\right]$$

$$= \frac{g_o}{E_{equiv.}D} \quad (A.5)$$

where subscripts P and R refer to paste and rock, respectively. Thus,

$$E_{equiv.} = 2\left[\frac{E_P E_R}{E_P + E_R}\right] \tag{A.6}$$

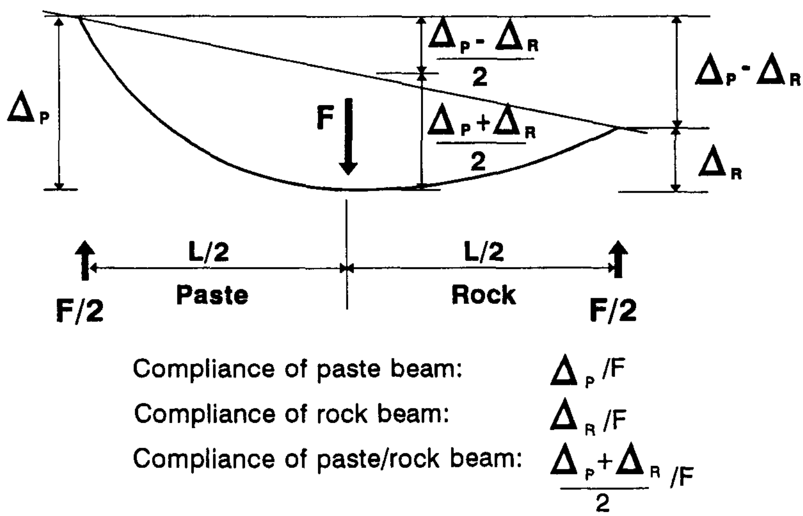

FIG. 4
Equivalent Compliance of Composite Beam