Bi-material fracture properties of concrete-concrete cold joints

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ABSTRACT: Repair and rehabilitation of concrete structures is a common requirement in the present day maintenance of infrastructures. Many concrete structures have been rehabilitated in order to extend their service life or to restore their original strength. An interface appears whenever a repair material is applied to a structure after rehabilitation. Usually, in a repaired system, the interface is relatively weaker than the material on either side of it. The performance of the repaired system is strongly dependent on the performance of the interface. In this work, experimental investigations have been carried out to study the fracture behavior and determine the fracture properties like fracture toughness and fracture energy of interfaces formed between different grades of concrete.

1 INTRODUCTION

Repair and rehabilitation of concrete structures is a common requirement in the present day maintenance of infrastructures. Compatibility between repair material and substrate concrete is important for prevention of cracking and stability of the repaired system. The review of literature in this area shows that reliable quantification of the required parameters such as the fracture properties of an interface is lacking, which are necessary in the design of an efficient repair system. There is very little information about the cracking and fracture process at the interface between old and new concrete.

Furthermore, in large concrete structures involving mass concreting such as dams, nuclear containment vessels etc., cold joints between successive lifts are inevitable. The cold lift joints behave as a bimaterial interface even though the grades of the concrete on either side of the joint is the same because of the heterogeneous nature of concrete. The interface between the cold lift joints form one of the potential sites of crack formation leading to weakening of mechanical strength and subsequent failure. Hence, it is important that proper mechanical behaviour of the interface is understood. Therefore, the present investigation has been under taken to obtain the fracture parameters such as Mode I and Mode II fracture toughness and fracture energy of the interface between different grades of concrete and to understand their fracture behaviour.

In repair of concrete structures, it is very commonly found that the interface formed between the parent and repair material contain concrete of different elastic properties, thus forming what is termed as a bi-material interface. Fracture at a bi-material interface is essentially mixed-mode, even when the geometry is symmetric with respect to a crack and loading is pure Mode I. This is due to the differences in the elastic properties across an interface which would disrupt the symmetry (Carlsson and Prasad 1993). Consequently, both tensile and shear stresses act on the interface ahead of the crack and opening and sliding displacements of the crack flanks occur behind the crack tip. The linear elastic solutions of the crack tip stress and displacement fields show that the stresses ahead of the crack front and displacements behind the crack front behave in an oscillatory manner. Due to this oscillatory behaviour, the definition of the stress intensity factors needs special consideration, and in addition crack face contact may occur at some short distance behind the crack tip. The mode I and mode II stress intensity factors cannot be decoupled to represent tension and shear stress fields as seen in the case of homogeneous materials.

The modes of failure and structural performance of a bi-material system is directly related to the properties of the interface between the constituent materials. Therefore, development of advanced materials with improved toughness and durability requires a fundamental understanding of the behaviour of the interfaces. Several test specimens have been proposed to measure the fracture properties such as fracture toughness and fracture energy of interfaces. An early experimental study on the measurement of the fracture toughness of mortar-aggregate interfaces in concrete was performed by Hillemeier and Hilsdorf (1977). They have reported test results for cases involving mode I loading conditions and have determined the fracture toughness using wedge loaded compact tension specimens. Suo and Hutchinson (1989) have used sandwich test specimens for measuring the interface crack toughness. Three-point bend beams, containing a vertical interface between two materials (austenite and ferrite) were made and tested by Tschegg et al. (1990) in order to study the behaviour of interface cracks. Bruhwiler and Wittmann (1990) have proposed the wedge splitting tests in order to perform stable fracture mechanics tests on concrete and concrete-like materials. Stable fracture mechanics tests defines the complete load-deformation diagram with a descending branch after the peak response which are needed for the determination of fracture mechanics properties. Buyukozturk and Lee (1993) have presented an interface fracture mechanics based methodology to assess the fracture toughness of mortar-aggregate interfaces. Two types of sandwich specimens, one a four point bending beam and the other a Brazilian disk specimen, wherein an aggregate layer is sandwiched between two mortar layers were tested to generate the fracture toughness curves of mortar-aggregate interfaces. Slowik et al. (1998) have done an experimental investigation on the mixed-mode response of concrete interfaces. In their work, large simulated rock/concrete rectangular bimaterial specimens were subjected to the complex stress field that exists along a dam/foundation interface in a gravity dam. A new retrofitting technique based on material compatibility with concrete has been developed at Cardiff University (Alaee and Karihaloo 2003b) that overcomes the problems associated with techniques based on externally bonded steel plates and FRP laminates which are due to the mismatch of their tensile strength and stiffness with that of the concrete being retrofitted. The authors have described the technology necessary for preparing high-performance fiber-reinforced concrete mixes designated CARDIFRC. To predict the moment of resistance of the beams retrofitted with CARDIFRC, an analytical model based on fracture mechanics approach has been proposed (Alaee and Karihaloo 2003a) which follows the initiation and growth of the flexural crack that eventually leads to the failure of the retrofitted beams. Chandra Kishen and Saouma (2004) have conducted wedge splitting tests on concrete-limestone interfaces in order to evaluate the mode I fracture energy. It was observed that the difference in the behaviour of an interface as compared to the intact material was in the post-peak load deformation response. Walter et al. (2005) have obtained a stress-crack opening relationship of steel-concrete interface using the wedge splitting tests through an inverse analysis. Their results have shown that interfacial cracking is dominated by the so-called wall-effect.

In this work, experimental investigations have been carried out to study the fracture behavior and determine the fracture properties like fracture toughness and fracture energy of interfaces formed between different grades of concrete.

2 THE WEGDE SPLITTING TEST

A possible problem associated with the use of the three-point bend beam is that when the size of the beam tested is relatively large, the effect of self-weight of the beam on the material fracture parameters should be very carefully evaluated. To overcome this problem, an alternative method using a wedge splitting test, which may be regarded as a "compact" three-point bend beam has been proposed by Bruhwiler and Wittmann (1990) and shown in Figure 1.

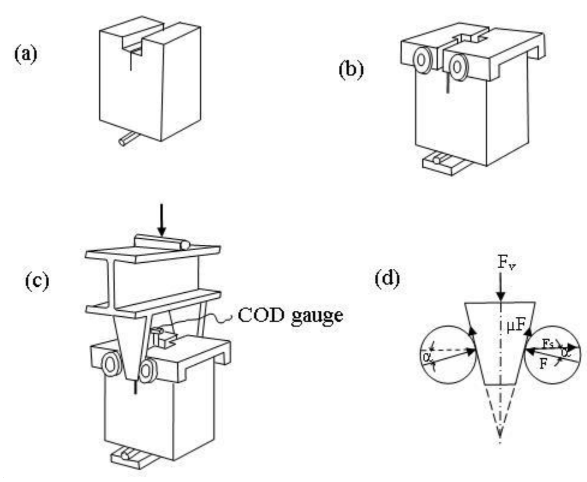

Figure 1: Wedge splitting device

Wedge splitting specimens having a transverse cold

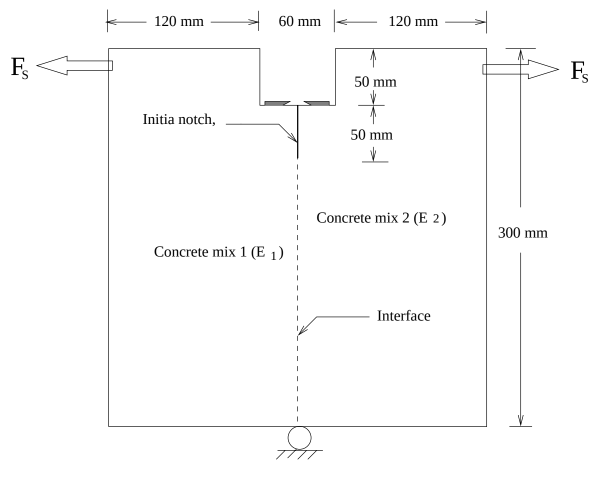

Figure 2: Geometry of the wedge splitting specimen

Table 1: Mix proportions for Different Grades of Concrete

No.	Mix Designation	Mix Proportion
1	A	1:3.20:3.49:0.70
2	B	1:2.29:2.76:0.56
3	C	1:2.59:2.22:0.45
4	D	1:2.27:1.97:0.40

joint between two different strengths of concrete are prepared and tested using the wedge splitting device. Figure 2 shows the geometry of the wedge splitting specimen. The width, height and thickness of the specimen are 300 mm, 300 mm and 100 mm respectively. The notch to depth ratio is 0.20. Four different concrete mixes designated as A, B, C and D and having the mix proportions as shown in Table 1 are used. In this table, the mix proportions shown are in the following order: cement : fine aggregate : coarse aggregate : water-cement ratio. Table 2 shows the average compressive strengths, modulus of elasticity and Poisson's ratio obtained for the different grades of concrete. In this table, concrete mix A^* has the same mix proportions as concrete mix A but the mechanical properties differ since it is prepared on different days. Concrete mix A^* is prepared while casting the first portion of the beams while mix A is prepared two days later.

2.1 Specimen Preparation

The wedge splitting specimens are prepared by casting the first half with concrete mixes A, B, C and D. The second half of the specimen with concrete mixes A, B, C and D is cast after two days over the first half. This creates a cold joint between the two grades of concrete. A total of sixty specimens are prepared, fifteen each with the first half containing concrete mixes A, B, C and D respectively. This means that specimens with interface combination, for example, AB and BA were prepared in order to study the effect of casting a higher strength material over a weaker strength material and vice versa. Intact control specimens (without interface) with concrete mixes A, B, C and D are also prepared. The surface of the first half which comes in contact with the second half is cleaned with a fine wire brush before the second half portion of concrete is poured. A notch is introduced at the interface during casting process itself by placing 2 mm thick card board at the desired location. The specimens are demoulded after two days of casting the second half and placed in water for curing.

Table 2: Mechanical properties for different grades of concrete for wedge splitting test

Mix Designation	Compressive Strength (MPa)	Elastic Modulus) (GPa)	Poisson's Ratio
A^*	20.1	22.4	0.20
A	21.1	22.9	0.20
B	32.2	28.4	0.19
C	41.9	32.4	0.18
D	52.8	36.3	0.18

2.2 Testing of Wedge Splitting Specimens

The wedge splitting specimens were taken out of water after 28 days of curing, cleaned and allowed to dry in shade for a few hours and white washed for testing. Figure 2 shows the loading and supporting arrangement for the wedge splitting specimen. The specimens were tested in a closed-loop servo hydraulic testing machine under crack mouth opening displacement (CMOD) control. The CMOD was monitored using a clip gauge. The clip gauge was mounted across the notch on 2 mm thick steel plates having a sharp edge and glued to the crack mouth. The load was applied through the principle of wedge splitting mechanism as shown in Figure 1 such that the specimen is under tension. The specimen is supported at the bottom on 25 mm diameter steel roller.

2.3 Results of Wedge Splitting Tests

Typical load-CMOD plots were obtained from the tests. Figure 3 shows the crack pattern in a typical specimen. Figures 4 and 5 show typical plots for the interfaces AB, BA and AC, CA respectively. The maximum load carrying capacity and the fracture energy of the wedge splitting specimens for various combination of interfaces are shown in Table 3. The fracture energy is computed from the area under the load-CMOD curve. Detailed conclusions on these results are presented in the last section.

2.4 Discussion on Results of the Wedge Splitting Tests

The following observations are made from the results of the wedge splitting tests on interfaces:

1. The maximum load carrying capacity decreases when the difference in the strengths on either side of the interface increases even though the second material is of much higher strength. For example, it is seen in Table 3 that the maximum load carrying capacity of specimen with interface designated as AB is greater than the maximum load carrying capacity of the beam with

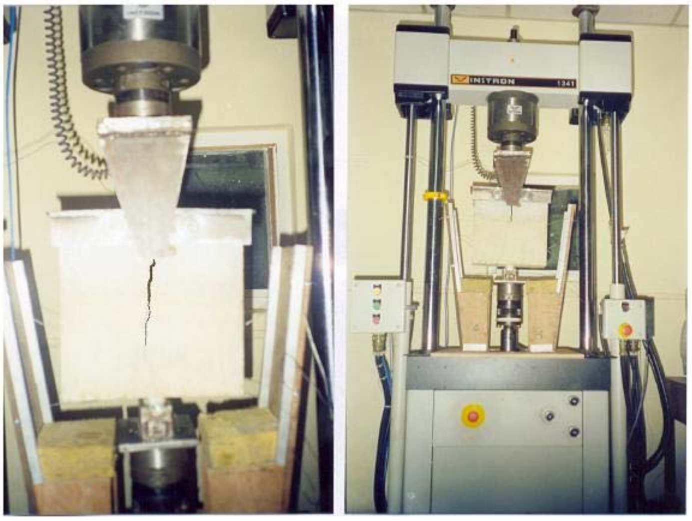

Figure 3: Crack pattern in wedge splitting specimen

interface designated as AC or AD, even though the strength of C or D is greater than that of B.

2. When the elastic modulus or the compressive strength of the first part of the specimen increases, the maximum load carrying capacity decreases. For example, the maximum load carrying capacity of specimen with interface designated as AB is higher than that having interface

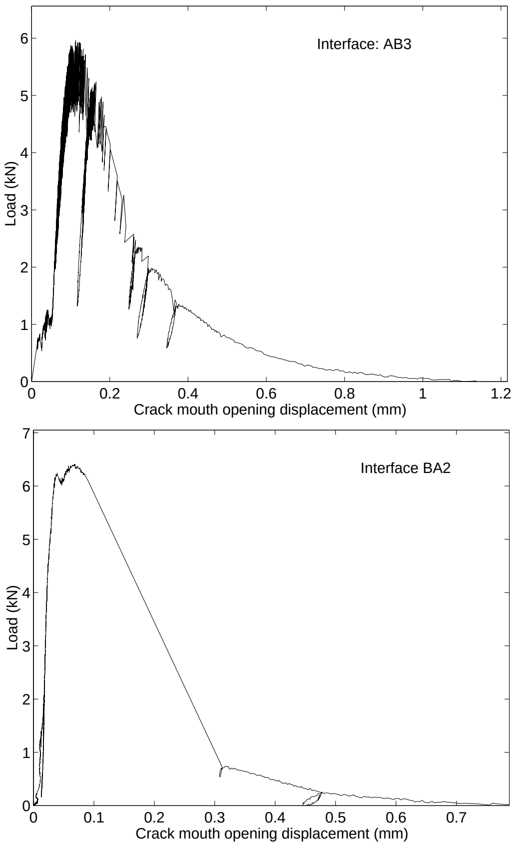

Figure 4: Load versus CMOD plot of wedge splitting specimens for interfaces AB and BA

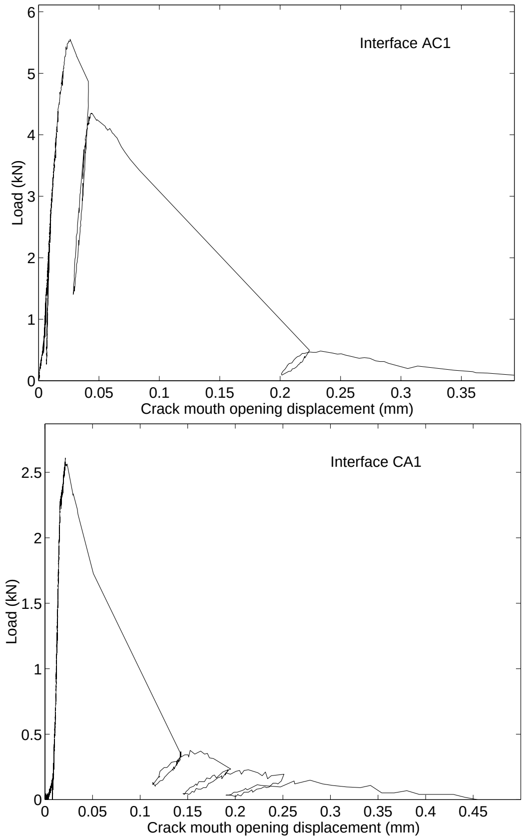

Figure 5: Load versus CMOD plot of wedge splitting specimens for interfaces AC and CA

Table 3: Average maximum loads and fracture energy G_F for the wedge splitting specimens

No.	Designation of interface	Maximum Load (kN)	Fracture Energy N/m
1	Intact A	7.331	108.85
2	AA	6.575	87.50
3	AB	6.015	82.29
4	AC	5.575	74.90
5	AD	5.412	72.68
6	Intact B	9.075	145.45
7	BA	6.139	51.66
8	BB	6.390	56.29
9	BC	5.164	49.32
10	BD	4.404	41.72
11	Intact C	10.950	165.87
12	CA	2.605	27.08
13	CB	3.001	34.34
14	CC	3.948	40.33
15	CD	3.418	34.97
16	Intact D	11.898	177.27
17	DA	1.810	21.37
18	DB	2.180	24.05
19	DC	3.515	27.13
20	DD	3.420	27.41

designation CB or DB, even though the compressive strengths of C and B are higher than that of A, as seen from Table 3.

3. For interface specimens having same material on either side, the maximum load carrying capacity decreases as the strengths of the material increases. Comparing interface specimens AA, BB, CC and DD, it is seen from Table 3 that the maximum load carrying capacity has the following trend: AA $>$ BB $>$ CC $>$ DD. The reason for this behaviour is due to the fact that higher strength materials are relatively more brittle than lower strength cementitious materials.

4. The fracture energy of interfaces AA, BB, CC and DD follow a decreasing trend. This decrease is much higher than the corresponding decrease in maximum loads. This implies that the slope of the softening portion of the load-CMOD curve has an increasing trend indicating that interfaces between like materials of higher strength are more brittle than those interfaces formed between lower strength materials. Similar behaviour is observed for intact materials as seen in Table 3.

3 FINITE ELEMENT ANALYSIS

The finite element analysis was conducted on the wedge splitting specimen using INterface FrActure MEchanics (*INFAME* code developed locally (Darunkumar Singh 1999)). This code has the capabilities of evaluating the stress intensity factors of cracks present in between the interface of bi-material systems. An oscillatory type of singularity is present at the bi-material interface crack (Rice and Sih 1965) as compared to the inverse square type singularity in a homogeneous single material. This has been accounted for in the present analysis while computing the bi-material stress intensity factors. The finite element formulation is based on the traditional displacement method. The stress intensity factors are obtained using the contour integral method (Hong and Stern 1978) based on Betti's reciprocal work theorem. As the stress intensity factors are extracted in terms of integral involving tractions and displacements on contour remote from the crack tip, six/eight noded elements are used for all the problems considered and no special elements are used. Contours are taken along the Gaussian stations. Contours could also be taken along the element edges, but this is purposely avoided as it will necessitate the extrapolation of stresses thereby inducing more approximation. Also closely spaced contours can be taken if the contour paths are allowed to pass through the Gauss points.

The compliance method (Bruhwiler and Saouma 1990) is used in the analysis wherein an effective crack length "a_{eff}" which is longer than the true crack but shorter than the true crack plus the fracture process zone (Figure 6) is determined by finite element calibration. A series of analysis with different crack lengths, starting with the initial notch are performed. In these analyses the actual values of the elastic moduli of the two concrete materials on either side of the interface as determined experimentally are considered. From each analysis the compliance and the stress intensity factors are determined in terms of the crack length. The stress intensity factors are determined using the Stern contour integral method in the finite element program *INFAME* for bimaterial specimens. A numerical compliance versus crack length curve is plotted. In addition, the mode I and mode II stress intensity factors (SIF) versus crack length curves are plotted for each analysis. These SIF curves are obtained for unit load and different crack lengths.

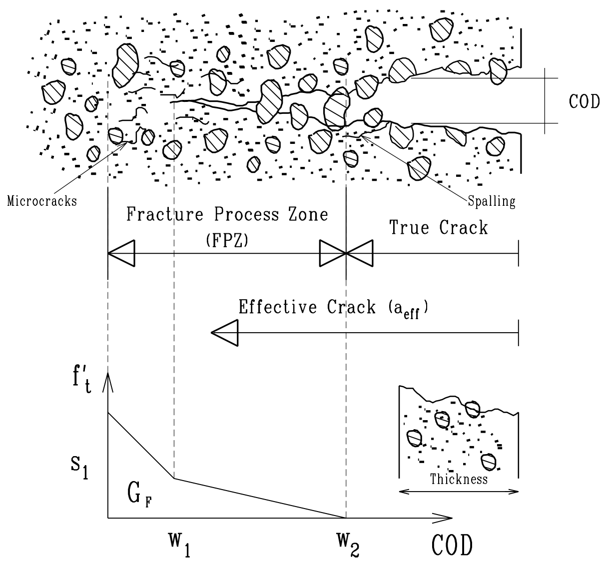

Figure 6: Geometrical parameters of notched interface beam

For each test, the effective modulus of elasticity is determined using the relation (Bruhwiler and Wittmann 1990) :

$$E_{eff} = \frac{C_n^o}{C_{exp}^o} \quad (1)$$

where C_n^o is the initial numerical compliance of the notched specimen without crack and C_{exp}^o is the initial compliance of the experimental splitting load versus CMOD curve. In doing so, the finite element calibration yields a normalized compliance C_n equal to

$$C_n = E_{eff} C_{exp} \quad (2)$$

In the experiments, a series of unload/reload versus CMOD readings are measured. From these unload/reload cycles the experimental compliance is measured and the numerical compliance computed using Equation 2. Using the compliance curve, the effective crack length is extracted. From this value of the effective crack length, the stress intensity factors, K_1 and K_2 are obtained from SIF curves. In this procedure, through a linear regression the following relations are numerically approximated;

$$a_{eff} \simeq a_{eff}(C_n) \quad (3)$$

$$K_1 \simeq K_1(a_{eff}) \quad (4)$$

$$K_2 \simeq K_2(a_{eff}) \quad (5)$$

where a_{eff} is the crack length. As mentioned in the experimental studies in the previous section, interface combinations, for example, AB and BA were prepared in order to study the effect of casting a higher strength material over a weaker strength material and vice versa. Analyses were done on similar combination in order to extract the fracture properties. Figure 7 shows the finite element mesh of the wedge splitting specimen. The numerical compliance curve for this beam is shown in Figure 8.

3.1 Results of the Numerical Analysis

Using the numerical compliance curve (Figure 8) together with the experimentally observed compliance, the effective crack length is determined at different stages of loading. Using this effective crack length, the stress intensity factors, K_1 and K_2 are obtained from the SIF curves shown in Figure 8. These SIF curves are obtained for unit load and different crack lengths. The analysis was carried out for all the three different sizes of the beams. The mode I and mode II fracture toughness values obtained for each unload / reload cycles were averaged to obtain the critical fracture toughness for the specimen, which are summarized in Table 4.

3.2 Discussion on the Results of Numerical Analysis

The following observations are made from the numerical analysis of the wedge splitting specimens:

1. The Mode I fracture toughness of the interface decreases when the difference in the strengths on either side of the interface increases even though the second material is of much higher strength. For example, it is seen from Table 4 that the mode I fracture toughness of specimen with interface designated as AB is greater than that of specimen AC or AD, even though the strength of C or D is greater than that of B.

2. When the elastic modulus or the compressive strength of the first part of the specimen increases, the Mode I fracture toughness decreases. For example, the mode I fracture toughness of specimen with interface designated as AB is higher than that of CB or DB, even though the compressive strengths of C and B are higher than that of A.

3. For interface specimens having same material on either side, the mode I fracture toughness decreases as the strengths of the material increases.

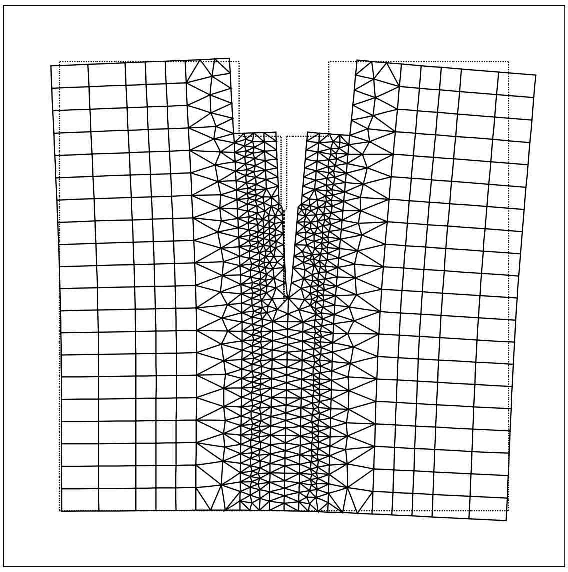

Figure 7: Finite element mesh of the wedge splitting specimen

Table 4: Stress intensity factors for wedge splitting specimens

No.	Designation of interface	K_1 [MPa$\sqrt{m}$]	K_2 [MPa$\sqrt{m}$]
1	Intact A	0.96	—
2	AA	0.76	0.00
3	AB	0.68	0.03
4	AC	0.56	0.06
5	AD	0.48	0.08
6	Intact B	1.15	—
7	BA	0.55	0.04
8	BB	0.63	0.00
9	BC	0.59	0.01
10	BD	0.32	0.02
11	Intact C	1.26	—
12	CA	0.23	0.03
13	CB	0.39	0.02
14	CC	0.54	0.00
15	CD	0.51	0.03
16	Intact D	1.32	—
17	DA	0.11	0.03
18	DB	0.29	0.03
19	DC	0.32	0.04
20	DD	0.47	0.00

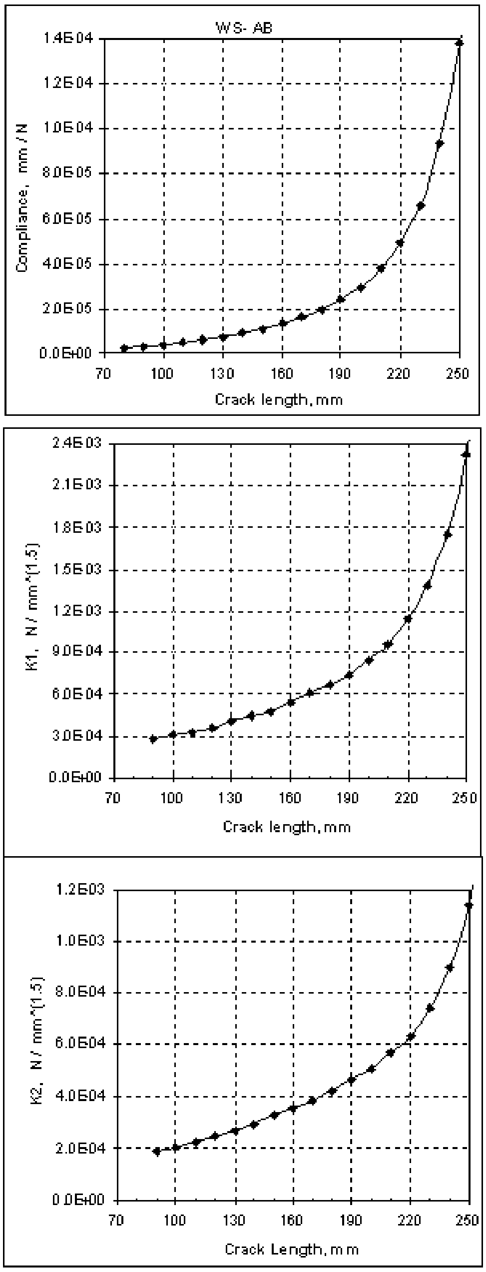

Figure 8: Compliance and SIF plots of the wedge splitting specimen

Comparing interface specimens AA, BB, CC and DD, it is seen from Table 4 that the mode I fracture toughness has the following trend: AA $>$ BB $>$ CC $>$ DD. This implies that higher strength cementitious materials are relatively more brittle than lower strength cementitious materials.

4. Even though the wedge splitting specimens were geometrically symmetric and loading was of pure Mode I, the presence of mode II fracture toughness confirms that mixed mode condition prevail at the interface of bi-material system, although the mode II component of fracture toughness is relatively small.

4 CONCLUSIONS

In this work, experimental and numerical investigations have been carried out to study the fracture behavior and to determine the fracture properties like fracture toughness and fracture energy of interfaces formed between different grades of concrete. It is seen that the behavior of interfaces depends greatly on the difference in strength between the two materials on either side of it. This will have a direct bearing on the design of patch repaired concrete systems.

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