Optimizing fracture toughness of matrix for designing ductile fiber reinforced cementitious composites

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ABSTRACT: Ductile fiber reinforced cementitious composites (FRCC) is usually designed by using high performance short fibers and allowing sufficient fiber-matrix bond strength, i.e. by enhancing the fiber bridging mechanism. However, matrices of high bond strength usually display high strength but low fracture toughness. In such a case, fibers may not be able to effectively bridge the initial crack and propagation of the crack is relatively brittle. Hence, an approach is proposed in which artificial microcracks are smeared in the matrix to optimize fracture toughness while preserving sufficient bond strength. Experiments were carried out in which alternative sources of microcracks were introduced into the composite admixture. Such approach showed promising capabilities for controlling ductility of the composite material, but its efficiency depends on suitable mix proportions. The experimental analysis was intended for development of procedures for optimization of the composite mixture for higher ductility, as well as identifying key parameters to control ductility of the composite.

Keywords: fracture toughness, ductility, material optimization, bond strength, toughening mechanisms

1 INTRODUCTION

Concrete is extremely versatile and can be made from several readily available constituents. In addition, it possesses good resistance to water and fire, as well as good durability in aggressive environments. Consequently, concrete is the most widely used engineering material. Constant increases in size of concrete members led advances in concrete technology particularly focused on developing high-performance concrete, which possesses high compressive strength and durability. Yet, concrete has two main detrimental properties as structural material, namely low tensile strength and poor fracture toughness. Gains in compressive strength have usually resulted in even lower strain capacity and resistance to crack propagation.

Recent concerns in concrete design are shifting towards safety and durability of concrete structures. Consequently, concrete technologies have branched into design of pseudo-ductile materials. The use of fibers in the composite matrix emerged as strategy to partially offset the low strain capacity of concrete. Though fibers improve post-peak mechanical behavior, they were introduced mainly to arrest propagation of cracks. The presence of fibers results in minimal increase in stiffness prior to cracking and holds the matrix together after cracking. During initial stage of loading, the fiber-matrix interaction is elastic, with stress transfer occurring through shear at the interface. As the load increases, shear may gradually destroy the chemical bond along fiber and matrix interface. Debonding activates a combination of elastic and frictional stress transfer mechanisms. Hence the fiber keeps bridging the crack until one of its ends is completely extracted from the matrix or the fiber breaks. Pullout of the fiber is preferred as a toughening mechanism since it consumes much more energy and prevents catastrophic failure. The role of toughening mechanisms is to consume energy, thus increasing the total energy required for fracture. Hence, fiber pullout may be regarded as a complex two-phase toughening mechanism. The first phase may be described as the work done in destroying the bonds between the matrix and fiber and the second phase as the work done by sliding friction while the fiber is extracted from the matrix. Several approaches have been proposed to improve the toughening mechanism of fiber reinforcement, in which the key element was increase of bond strength and friction at fiber-matrix interface.

Developing other energy consuming mechanisms in concrete may further increase its fracture toughness. Some recently proposed approaches include tailoring of the matrix composition and particle size. Complexity arises in tailoring cost-effective composite taking into consideration the wide range of mechanical, physical and chemical properties of fibers, as well as properties of different particulate matrices. The resulting fiber reinforced cementitious composites (FRCC) may display somehow distinct mechanical behavior and failure mechanisms. Appropriate choice will depend on application but in any case it will result in an individual optimization problem, in terms of amounts and size of components, for each particular choice of components in the mixture.

This study investigates an alternative toughening mechanism based on "microcrack formation". The basic principle is the uniform distribution of fictitious microcracks in the composite matrix. As a source of fictitious microcracks, mica flakes were introduced in the composite mixture. Hence by controlling size and content of the mica flakes (fictitious microcracks) in ways to maintain stable cracking propagation, additional energy may be consumed in developing a number of concurrent crack surfaces. Note that the mechanism here is not identical to toughening mechanisms of microcrack formation in the fracture process zone (FPZ), as usually described in the literature (Flinn & Trojan, 1995). Although little energy may be consumed by redistribution of stresses, significant amount of energy may only be consumed with activation of pullout mechanisms in larger number of fibers, and so producing a pseudo-ductile behavior.

2 EXPERIMENTAL PROCEDURE

In this study, series of three-point bending tests were performed on notched specimens as shown in Figure 1. The specimens consisted of square beams with 40x40x160 mm of dimensions and made of HCP (hardened cement paste) or FRCC. Notches, whose depth was 20 mm for HCP and 10 mm for FRCC, were introduced at the mid-span of the beams. Tests were carried out using an ISTRON-5567 Universal Materials Testing Machine, at a loading speed of 0.2 mm/min, with measurement of

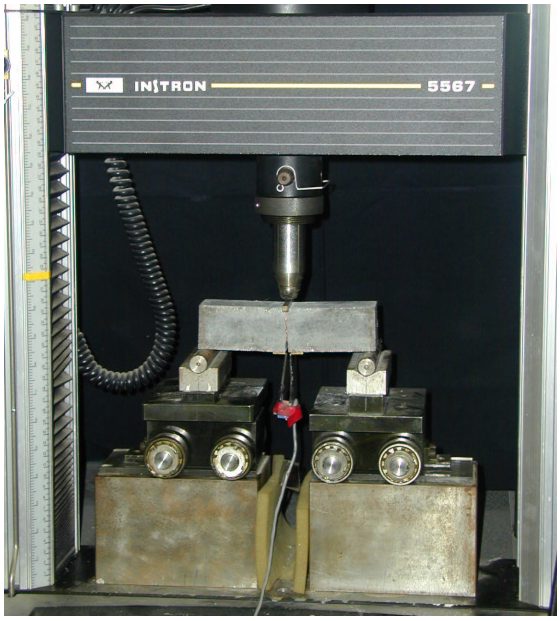

Figure 1. Three-point bending test setup

load-CMOD (Crack Mouth Opening Displacement).

The tests may be separated into two groups according to the purpose. The first group of tests was performed to measure the fracture toughness parameter (J_{IC}) of HCP specimens, whose components constitute also the matrix of the FRCC specimens. Hence, different contents of mica flakes were added to the composition to investigate the effect of mica flake in the properties of the matrix. In the second group of tests, the water-binder ratio (W/B) as well as the content and size of mica flakes were varied in the composition of FRCC specimens, to investigate the effect of these changes into the energy consumption.

2.1 Materials and Mix Proportions

Mica flakes were introduced into the composition to functionally act as microcracks. Mica is generic name for a group of complex aluminosilicate minerals having laminate structure with different chemical compositions and physical properties. It has nearly perfect basal cleavage in the direction of the large surfaces, which permits splitting easily into optically flat films, as thin as one micron in thickness. Even after splitting the thin films remain tough and elastic even at high temperature.

For the FRCC, a special type of polyethylene fiber (Dyneema® SK-60) developed by Toyobo was employed. The fiber is produced out of ultra-high-molecular weight polyethylene (UHMWPE)

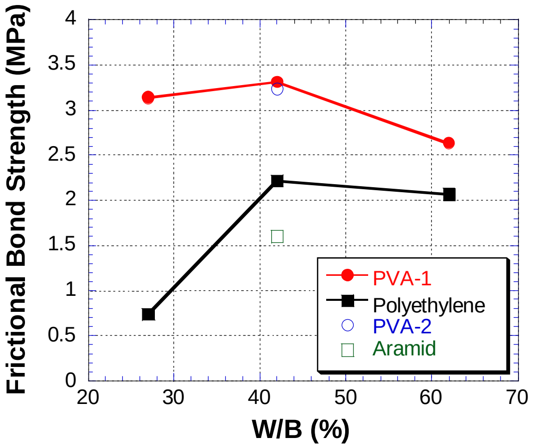

Figure 2. Comparison between frictional bonds of four different fibers (2 PVA fiber types, 1 Aramid and the SK-60 polyethylene fiber)

and exhibits high strength, high modulus, high abrasion resistance and low density. Pullout tests in previous research (Kiyota et al. 2002) show that the chemical bond between this fiber and matrix is apparently very low or ineffective. The frictional resistance at the interface between fibers and matrices with normal to high W/B seems significantly strong. However, for low W/B the frictional bond seems substantially reduced (see Fig. 2). Mechanical and geometrical properties of the fiber are displayed in Table 1.

Table 1. Fiber properties

L (mm)	Ø (μm)	ρ (g/cm^3)	f_t (Gpa)	E (Gpa)
30	12	0.97	2.77	88

The composite binder (B) constitutes of early strength Portland cement (C) and silica fume (SF). Three different particle sizes grading of fine mica flakes (MF) were employed alternatively in the compositions to investigate the effect of different sizes of microcracks. The Fuller distribution for the three grading, identified by their respective average sizes (55, 160 and 620 μm), is presented in Table 2.

Table 2. Fuller distribution of mica flakes

Mesh	AS-55	AS-160	AS-620
850μm	–	0.2	5.0
425μm	–	32.0	75.0
212μm	0.8	77.0	97.0
106μm	10.0	95.0	↓
63μm	40.0	↓	
45μm	60.0		
Accumulated	100.0	100.0	100.0

Since a superplasticizer (SP) is required to attain workability of the FRCC, the same amount of SP was added to the HCP specimens in order to match the composition of the matrix of FRCC specimens. Table 3 shows the mix proportions for HCP and FRCC specimens.

Table 3. Mix proportions of testing specimens

Proportions	HCP	FRCC
C : SF	79.3 : 20.7 (vol. %)	
SP / B	2.0 (wt. %)	
W / B	30, 40, 50 (wt. %)	
MF / B	0.0, 1.0, 2.5, 5.0 (wt. %)	
PE	0.0	1.5 (vol. %)

2.2 *Experimental Analysis Method*

For evaluating J_{IC} (critical energy release rate) of matrix specimens in the first series of three-point bending tests, the fracture toughness K_{IC} was determined from the maximum bending load (P_{max}) using equation (1) proposed by Srawley (1976):

$$K_{IC} = \frac{P_{max} s}{b d^{3/2}} f_b , \qquad (1)$$

where s is the span between support reactions; b and d are the thickness and depth of the beam, respectively; and f_b is the geometry correction for bending load, given as function of the ratio (α) between notch size and depth of the beam:

$$f_b = \frac{3\alpha^{1/2}\left[1.99 - \alpha(1-\alpha)(2.15 - 3.93\alpha + 2.7\alpha)\right]}{2(1+2\alpha)(1-\alpha)^{3/2}} \qquad (2)$$

Hence, for the case of HCP, LEFM may be assumed and G_{IC} may be readily calculated by Equation (3), where E is the elastic modulus of the HCP specimen.

$$J_{IC} \approx G_{IC} = \frac{K_{IC}^2}{E} \qquad (3)$$

For evaluating ductile behavior of materials, simple measurements of areas of deformation energy are relatively insensitive to the shape of the load-displacement curves. On the other hand, energy ductility indices such as U_u/U_p (energy at failure/ energy at peak load) or U_{cp}/U_{ci} (energy to crack propagates/energy to crack initiates) as well conventional ductility index used for metals and/or RC members such as δ_u/δ_y (deformation at failure/deformation at yielding) may be somehow cumbersome to be employed for designing ductile FRCC. The apparent "yielding point" on the pseudo-ductile behavior of FRCC is not so clearly defined as in metals. Similar drawback may arise with existent energy indices, since FRCC may present two peak loads of similar magnitude – one at very low deformation (due to strong chemical bond and/or high-strength matrix) other at substantially larger deformation (due to strong frictional bond) – sometimes separated by deep valleys as shown in Figure 3. Hence, the present study suggests an alternative index of ductility (I_D), which is related to the shape of the load-CMOD diagram for the target design and is relatively easy to be calculated. The target design in the case was idealized as rigid-perfect-plastic material, hence the design index of ductility is given as the ratio between the area below the curve of the load-CMOD diagram of the FRCC and the area of an idealized rigid-perfect plastic diagram with same displacement and peak load. Note that an elastic-perfect-plastic material would be more likely to be expected for the FRCC. However, since in FRCC elastic deformation may be expected to be very small compared to plastic deformation, the rigid-perfect-plastic diagram suits better for the design, in the sense that it penalizes design approaches which result in great loss of stiffness. Note also that due to limitations on the clip gage capacity, load-CMOD curves as well as measurements stop at the limit value of 5 mm CMOD.

Figure 4 shows an example of application of the index of ductility I_D for two hypothetical materials with same fracture energy.

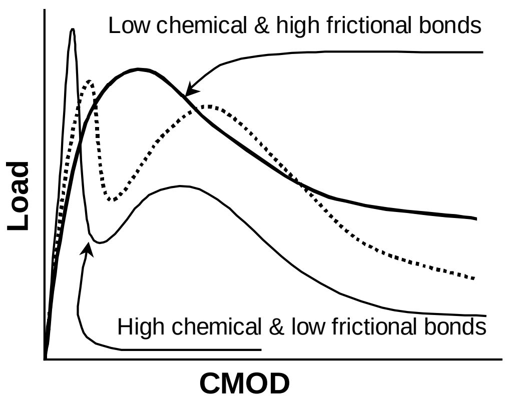

Figure 3. Typical load-CMOD curves of FRCC with different bond characteristics

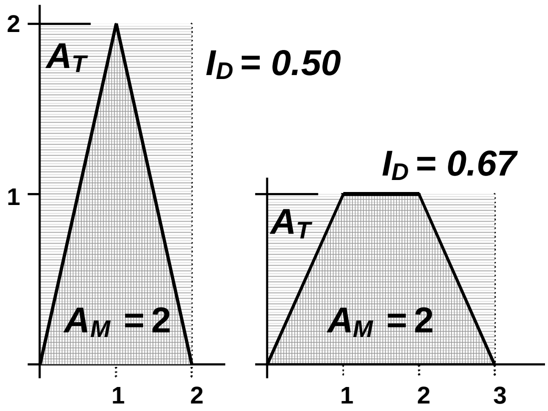

Figure 4. Evaluation of indices of ductility I_D (A_M/A_T) for two hypothetical load-CMOD curves exhibiting identical value of fracture energy but different shapes.

3 RESULTS AND DISCUSSION

Figure 5 present curves relating J_{IC} and mica flake content for matrices (HPC) with different water-binder ratio. All curves show a clear inflection, which suggests that mica flake at low contents may act as localized failure reducing the fracture toughness of the material. However, as the content increases they may also act somehow as reinforcement or other toughening mechanisms. In addition, it may be observed that the W/B exerts strong influence in the fracture toughness of the HCP. This is likely to be explained by the increase of the porous structure with the increase on W/B, and consequent reduction of strength.

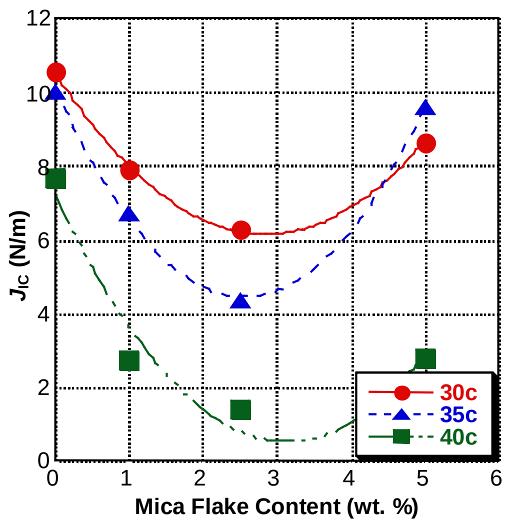

Figure 5. Curves describing the behavior of J_{IC} vs. mica flake content for HPC specimens with 3 different W/B.

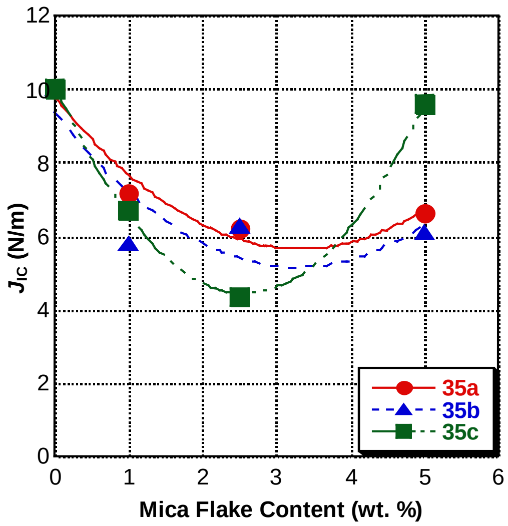

Figure 6. Curves describing the behavior of J_{IC} vs. content mica flake of different size distributions: “a” (AS-620), “b” (AS-160) and “c” (AS-55).

For the experiments results presented in Figure 6, the W/B was fixed at 35% and the influence of the mica flake size was investigated. The curves show that the finer flakes, at low contents, seems to act as imperfections while their short length do not allow them to provide localized reinforcement to the matrix or to promote substantial crack deflection. However, at high contents the finer flakes seem to be considerably more effective as toughening mechanisms. One explanation for this may be that different toughening mechanisms result from finer and from coarse flakes, e.g. the formation of FPZ by very fine flakes and the crack bridging or deflection by larger flakes. Other possible explanation is the homogenization of the material by uniform distribution of defects, and hence it could be achieved at lower contents of finer flakes than of coarse flakes. However, none of such effects may be actually proved without further assistance of numerical modeling and analyses.

Figure 7 show the effect of two different mica flake size distributions, types “a”(AS-620) and “b” (AS-160), into load-CMOD curves from bending tests of FRCC specimens. The use of mica flakes in the matrix of the FRCC, in most cases, seems to produce certain improvement in ductility, when compared to value of the index of ductility for the FRCC without mica flakes (I_D=0.591). Yet the mica flake type b produced very little effect. The values of I_D, which are displayed in Figure 7, were given in general by the average of 3 curves. However, for coarser size distributions of mica flake, the values of the 3 curves may vary a good extent.

The finer mica flakes (type “c”), when added to the matrix composition of the FRCC, resulted in indices of ductility of same order of type a. The poor performance of the intermediate size (type “b”), suggests that the toughening mechanism using coarse mica flake (type “a”) is different from that using fine mica flakes (type “c”). The mechanism in coarse mica flake (type “a”) seems more complex, and consequently more difficult to be identified. The fine mica flake (type “c”), on the other hand, seems not fit for crack bridging or crack deflection. Hence type “c” was preferred in this initial investigation. Figure 8 presents load-CMOD curves from experiments using mica flake type c, varying the content of mica flake and the water-binder ratio, in the composition of the FRCC matrix.

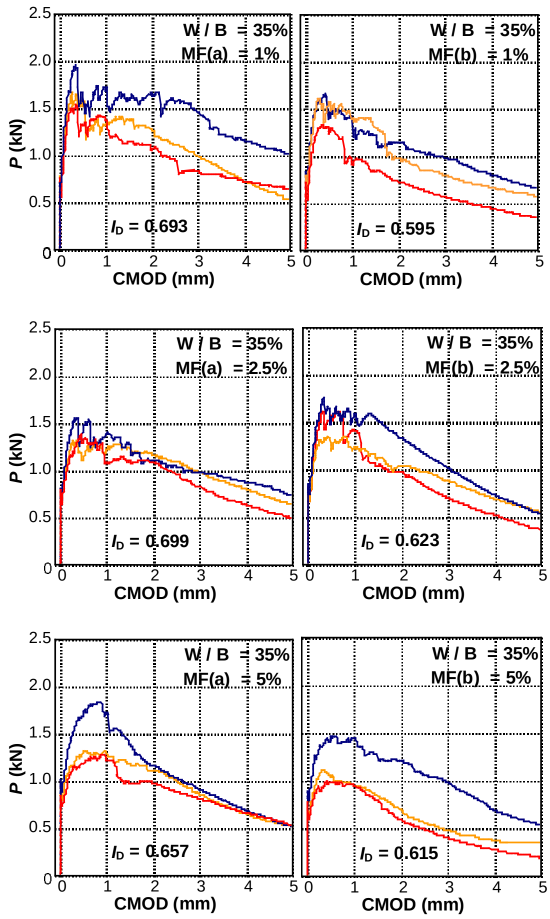

Figure 7. Comparison between load-CMOD curves of FRCC specimens with different content (1, 2.5, 5%) and size distribution (“a” and “b”) of mica flake.

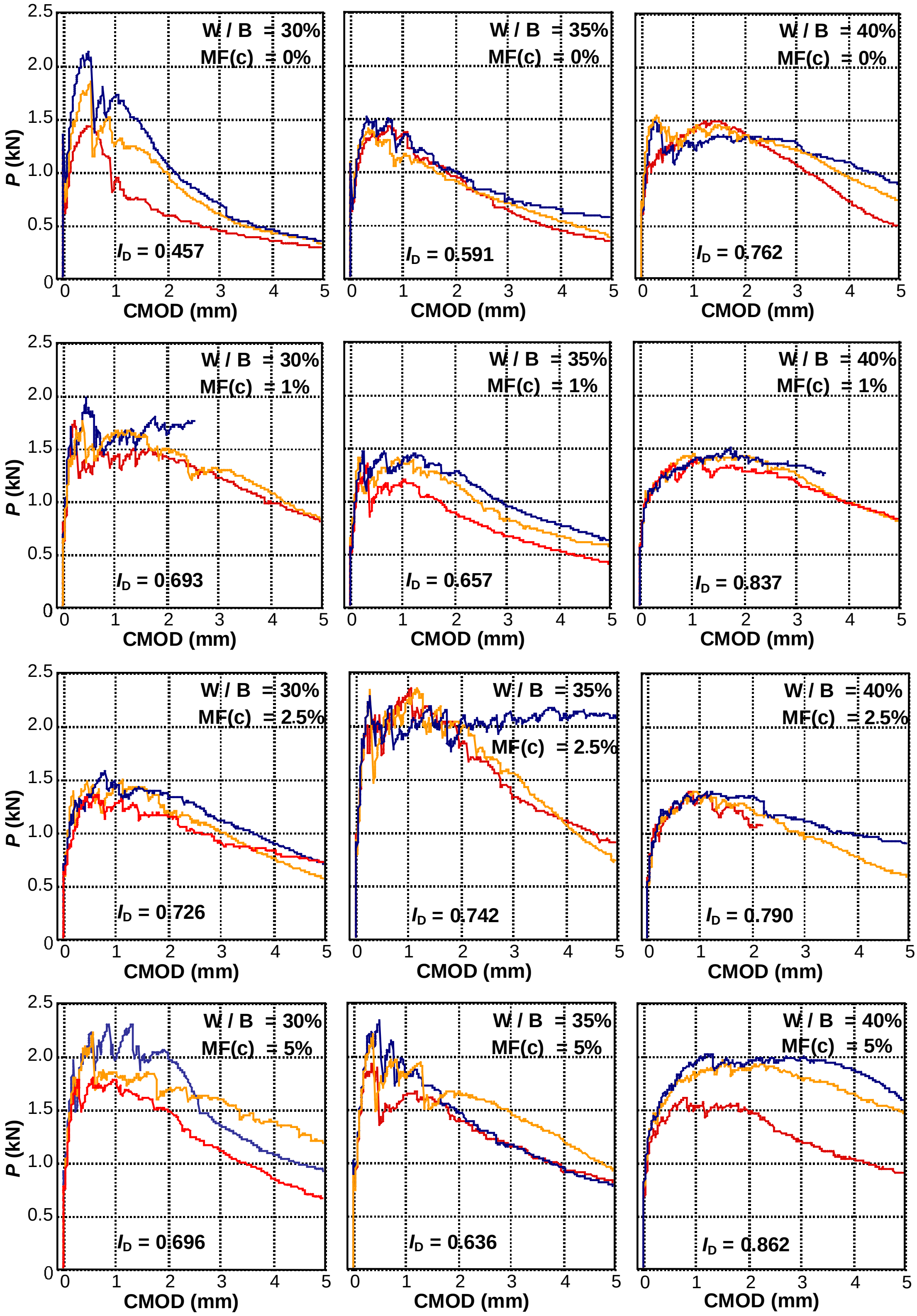

Figure 8. Load-CMOD curves of FRCC for different W/B and different mica flake contents in the FRCC mixture.

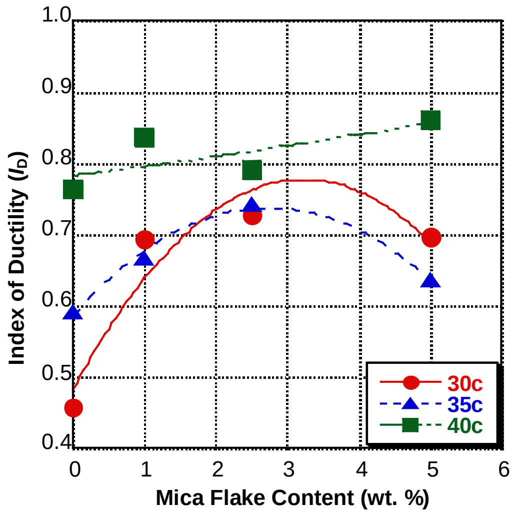

Figure 9. Ductile behavior of FRCC as function of the content of mica flake and value of W/B.

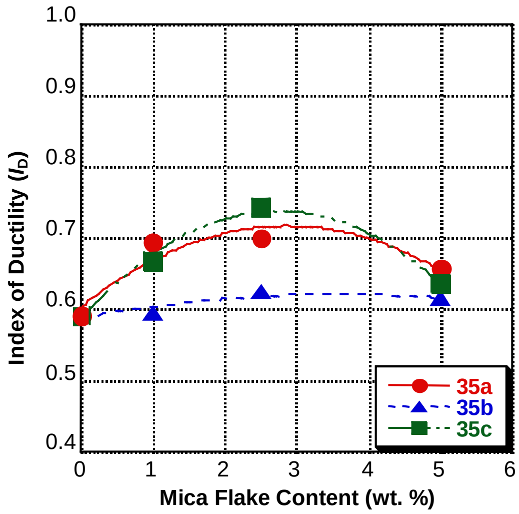

Figure 10. Ductile behavior of FRCC as function of the size and content of mica flake and fixed value of W/B.

The load-CMOD curves of FRCC without mica flake show clearly that the weakening of the matrix with the increase of W/B value results in gain in ductility and fracture energy (G_f). The addition of mica flake into the matrix composition, while the W/B was kept constant, resulted in further increase of ductility and fracture energy. The optimum value for the mica flake content may be dependent on value of W/B, though a clear trend was not yet identified. It seems that a key element for the design of ductile FRCC is to attain maximum energy consumption through fiber debonding. The reduction of matrix strength allows stresses being drifted away from the initial crack by promoting concurrent fine cracks. Hence, if rise in stresses can be relieved early in its development, the localized failure may be delayed. However, a straightforward method to determine how weak the matrix should be, i.e. an optimum value of the matrix fracture toughness, was not possible to be derived from the experimental results.

Figure 9 presents curves describing the ductility as function of the mica flake content for three W/B values. Then for lower W/B values a point of inflection in the curves between 2.5~3.5% content of mica flake present, while for a W/B value of 40% there was no sign of inflection even with 5% content. It may be possible that with at low W/B values the flowability of the mixture is affected and consequently the fibers may not be quite uniformly distributed. This remains to be experimentally investigated.

Figure 10 shows a good performance for mica flake types “a” and “c”. This may indicate that few relative large flaws (fictitious cracks), as well as large number of very fine micro-defects distributed in the matrix, may produce positive effects in the ductility of the FRCC. The crack pattern in Figure 11 (left) shows some large flakes of mica at the crack surface indicating that those have developed cracks. In such case, mica flake type “a”, it was observed considerable curving cracks. The crack pattern on the right, for mica flake type “c”, shows a development of parallel cracks along the fracture surface. In both cases the results seems a rather blunt cracking. In the case of mica flake type “b” at the center of Figure 11, little may be said but it seems that in this case there is a higher trend for

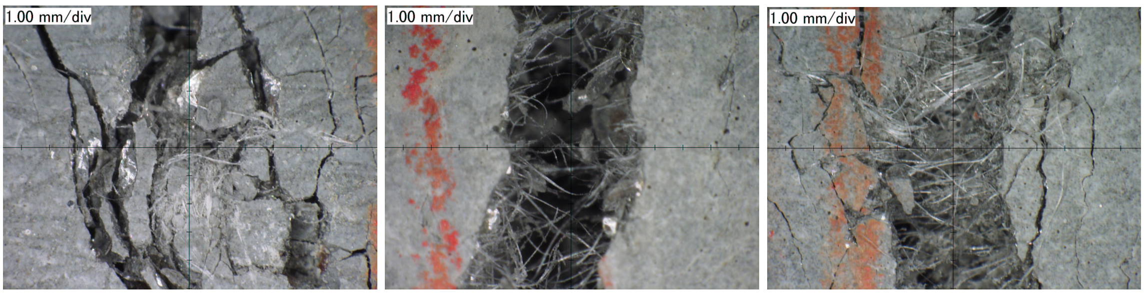

Figure 11. Crack opening in FRCC specimens with 5% content of mica flake of types a, b and c, respectively.

development of crack in areas of low fiber reinforcement.

4 NUMERICAL MODELING

Although the experiments show clear evidence on the positive effect of the mica flakes for the design of ductile FRCC, the inherent mechanism is far from being understood and controlled. Changes in W/B may affect the flowability, and consequently fiber distribution, orientation and bonding in the FRCC, as well as the microstructure and strength of the matrix. Addition of mica flakes to the composition may similarly reflect in changes into various parameters governing fracture and also introduce additional toughening mechanisms, such as crack arresting and blunting. For most cases, the parameters governing the fracture behavior cannot be isolated in experimental analyses. Numerical modeling and analyses are essential for the material optimization. A discrete model for simulation fiber pullout has been developed to investigate the influence of different mica flake size and content into debonding mechanics. Thereafter, the results will be introduced into a mesolevel model for concrete fracture simulation (Slowik & Leite 1999), whose generation mechanism is being adapted to generate a coarse porous media and mica flakes into the HCP matrix. This second stage of numerical modeling aims to investigate the differences in the mechanism of coarse and fine mica flakes; effects of fiber distribution and orientation; as well as optimum values of mica flake content for the design of ductile FRCC. Results of the numerical analyses are to be presented in subsequent publication.

5 CONCLUDING REMARKS

Crack formation is instinctively regarded as leading to failure because the remaining area of sound material undergoes higher stress. However, this analysis applies mainly to a single crack; concurrent crack may relieve localized stresses and slow the rate of crack propagation. In similar way, assuming that stronger matrix will result in stronger material may be proved wrong in the case of FRCC. The weakening of the matrix allows easier development of concurrent cracks, and consequently, more energy consumption. The results presented here show that the weakening of the matrix resulted in certain cases, even in a little increase in the peak-load value, as well as considerably more fracture energy and ductility. It

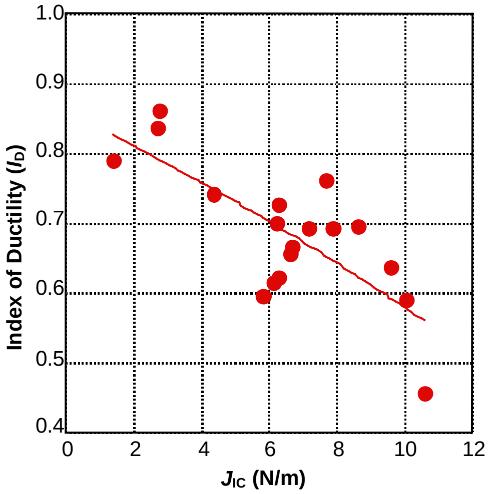

Figure 12. Relationship between ductility of FRCC and matrix fracture parameter J_{IC}

may of course depend on how "strength" is measured; hence in this study strength was assessed in terms of resistance to fracture, or fracture toughness. Figure 12 shows then strong evidence that the ductility of the FRCC increase with the decrease of fracture toughness of the matrix. The fracture toughness of the matrix may depend considerably on the W/B ratio, however the use of mica flake in the composition proved to be a promising approach to control fracture toughness of different matrices. Optimum values of mica flakes or fracture toughness may depend on fiber debonding characteristics and other parameters that can only be investigated with assistance of numerical analyses and simulations.

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