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Technical Note

Tensile strength enhancement in interground fiber cement composites

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Abstract

Interground fiber cement (IFC) is a new process where fibers are ground in with the cement clinker during the dry cement manufacturing process. With IFC considerable strength enhancement can be achieved compared to ordinary cement even at a fiber volume as low as 0.2% due to homogeneous fiber distribution and fiber surface modifications associated with the milling process. The cracking mechanisms associated with the strength enhancement were observed in real time during load application using a custom designed loading device. The homogeneous fiber distribution stabilizes crack growth. Formation of multiple, stable secondary microcracks was observed during the strain hardening regime, enhancing the strain capacity at ultimate strength. Fiber pullout was the dominant toughening mechanism in the strain softening regime. For fibers inclined to the propagating crack, fiber pullout was preceded by secondary microcrack formations along the fiber/matrix interface.

Keywords: Interground fibers; Cement mill; Polypropylene fibers; Crack propagation

1. Introduction

Fiber reinforcements can, in principle, be used to increase both the toughness and strength of brittle matrices. In conventional cement based fiber composites, (i.e. fiber reinforcements up to 2 vol%) strength enhancement is negligible. The fibers mainly contribute to toughness increase [1]. Naaman [2] and Shah [3,4] have shown that at high fiber volume fraction (in the range of 7–10 vol%) both the toughness and strength can be simultaneously improved. However, because fibers are far more expensive than cement, these composites are too costly for broad commercial use. It would, therefore, be highly desirable to achieve similar strength enhancements at far lower fiber volume fractions. This paper investigates the effect of interground fiber cement (IFC) on ultimate strength and strain enhancement. The cracking processes in IFC up to peak load and beyond were observed and monitored during load application. The surface modifications of polypropylene fibers due to the milling process are addressed.

The first part of the paper introduces the IFC process and addresses the surface modifications of polypropylene fibers due to the milling process. The second part presents results on strength and strain enhancement and in situ crack propagation measurements during the strain hardening and strain softening regime in IFC composites.

2. Interground fiber cement

2.1. IFC process

The IFC process is a new technique where fibers are ground in with the cement clinker during the dry cement manufacturing process. A unique feature of IFC is that as the cement fraction in the mix is increased, the fiber content increases automatically. Burrows [5] cites that high cement contents are one of the major causes of cracking in the field. With IFC a constant fiber-to-cement ratio is maintained. This represents a technological improvement over adding a fixed fiber quantity per cubic yard to fit various concrete applications regardless of cement content. From a quality control stand point, the cement lab technician can test the premixed IFC prior to

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shipment which eliminates the human factor when fibers are added at the job site by hand. The efficient cement mill mixes fibers more thoroughly than the low shear action of a truck mixer. Uniform fiber distribution is of utmost importance in achieving the full reinforcing values of fibers in cement based products. The modern cement mill's high efficiency air separator eliminates any fiber clumps or balls and distributes the fibers evenly within the cement. The IFC double mixing, first at the cement mill, and then again on the wet mix, results in a more uniform fiber distribution. Furthermore, IFC automatically multi-grades the fiber for reinforcing cementitious composites which are made typically of multi-sized aggregates and cement grains. The cement lab tests of IFC and "Sieved IFC" (Fibers sieved out of cement) are given in Table 1. The chemical analysis of the Sieved IFC is given in Table 2.

2.2. Fiber modifications

The physical data of the polypropylene fibers used in the IFC process are given in Table 3. The smooth surface of polypropylene fibers prior to the milling process is shown in Fig. 1. The interfacial bond between polypropylene fibers and cementitious matrix is weak because of their smooth fiber surface. There is no strength enhancement with polypropylene microfibers even at 5 vol% [6]. The IFC process modifies the fiber surface as shown in the SEM micrographs in Figs. 2 and 3. The milling process attaches and impregnates cement grains into the fiber surface (Fig. 2) making the polypropylene

Table 1
Quality control cement lab tests of sieved IFC (fibers sieved out of cement) and IFC

	Sieved IFC	IFC
Blaine fineness	Not tested	3050 cm^2/g
Sieve analysis % passing		
80 um	0.2%	0.1%
24 um	39.2%	36.6%
8 um	70.9%	68.5%
Volume stability	0 mm	0 mm
% H_2O of mortar	29.4	28.5
Setting time		
Initial	195 min	160 min
Final	240 min	210 min
Flow	82	85
Compressive strength		
2 days	22.5 MPa (3278 psi)	23.8 MPa (3467 psi)
7 days	33.3 MPa (4851 psi)	35.0 MPa (5099 psi)
28 days	43.9 MPa (6395 psi)	45.4 MPa (6613 psi)

Table 2
Chemical analysis of the sieved IFC (fibers sieved out of cement)

Composition	Weight percent (%)
SiO_2	20.74
Al_2O_3	5.00
Fe_2O_3	3.38
CaO	63.10
MgO	1.45
SO_3	2.35
Na_2O	0.25
K_2O	0.78
Cl	0.02
Ignition Loss	2.25
Insoluble Residue	2.25

Table 3
Physical properties of polypropylene fibers

Type	100% polypropylene
Length (mill)	12 mm maximum (multi-graded in cement)
Diameter	18 μm
Additional rate	0.3% By weight of cement ($>1\%$ cement vol.)
Fiber count	>330 millions/kg
Raw material	Polypropylene C3H6
Specific gravity	0.9–0.91
Absorption	Nil
Electrical conductivity	Low
Thermal conductivity	Low
Melt point	145°C (293 F)
Tensile strength	300 MPa (43,500 psi)

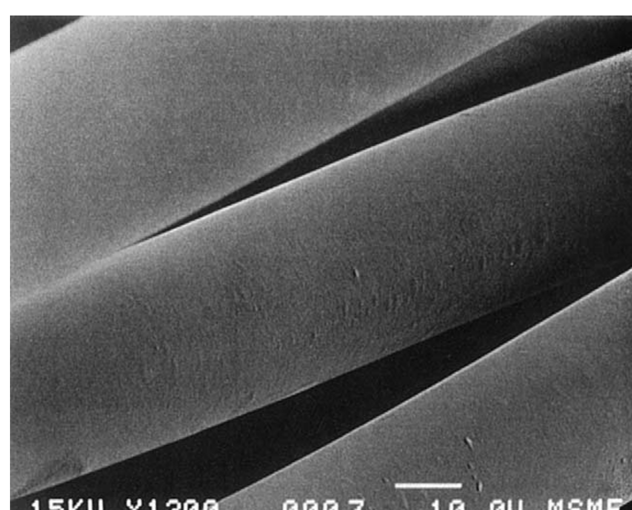

Fig. 1. SEM micrograph of polypropylene fiber surface before the milling process.

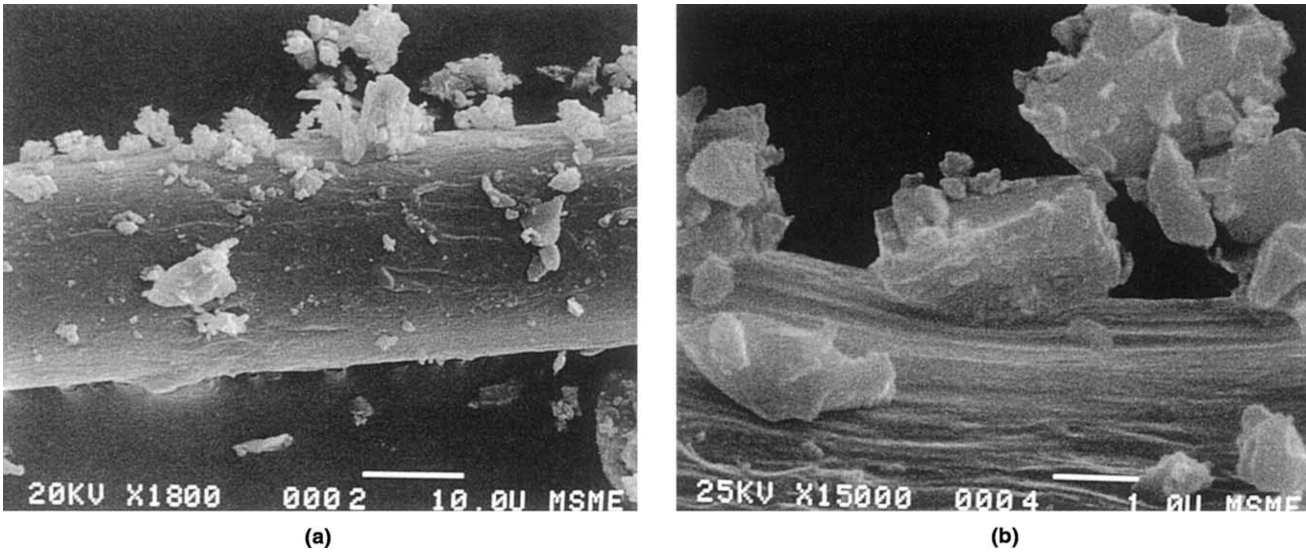

Fig. 2. SEM micrograph of cement grains impregnated into the fiber surface after the milling process: (a) at 1800 magnification, (b) at 15,000 magnification.

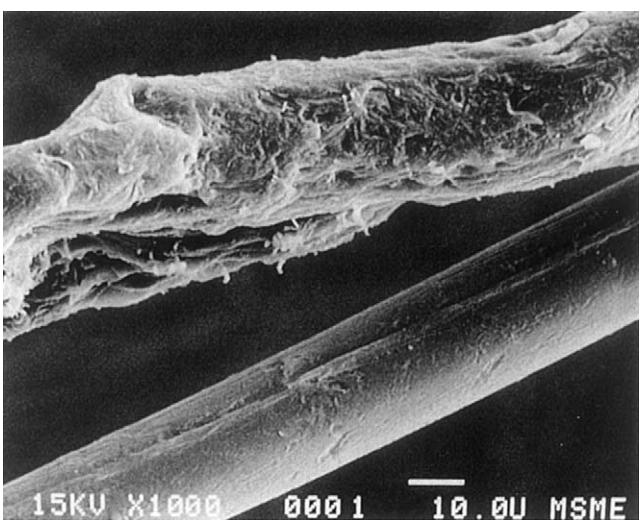

Fig. 3. SEM micrograph of fiber characteristics after the milling process. A small percentage of fibers are highly deformed as shown by the top fiber in micrograph; the majority of fibers show the characteristics of the bottom fiber in the micrograph.

fibers less hydrophobic which aids in the wet mixing action for uniform fiber distribution [7]. The cement grains when in contact with water will hydrate. The hydration products then form directly on the fiber surface enhancing the bond strength between the fibers and the matrix.

To examine fiber deformation and fiber surface roughness, the interground fibers were ultrasonicated in acetone to remove the attached and impregnated cement grains. A small fraction of the fibers are highly deformed after the dry milling IFC process as shown by the fiber at the top of the SEM micrograph in Fig. 3. The majority of the fibers, however are less deformed and reveal fiber surface characteristics shown by the fiber on the bottom of the micrograph in Fig. 3. The enhanced roughness of the fiber surface will enhance the frictional shear stress at the fiber/matrix interface. Kraai [8] found that IFC produced a better gripping action and 1.6 times greater tensile strength in the early stage of hydration (after 6 h) compared to specimens prepared with the typical wet mixed-in polypropylene microfibers.

3. Experimental procedure

3.1. Specimen preparation

IFC mortar specimens reinforced with 0.2 vol% of interground polypropylene fibers and mortar specimens without fibers (fibers sieved out of cement) used as control were fabricated with a w/c of 0.36, 10% silica fume and a sand to cement ratio of 2:1. The mortar control specimens and the fiber reinforced mortar composites were cast using 50 mm × 50 mm × 50 mm steel molds. After 28 days of curing at 100% relative humidity, the cubes were cut into compact tension specimens with a width of 40 mm and a thickness of 8 mm. After the specimens were notched and polished to ensure uniform thickness crack propagation measurements were performed under an optical microscope using a custom designed loading device.

3.2. Loading fixture and testing procedure

The loading device designed for crack propagation measurements is shown in Fig. 4 and described in more

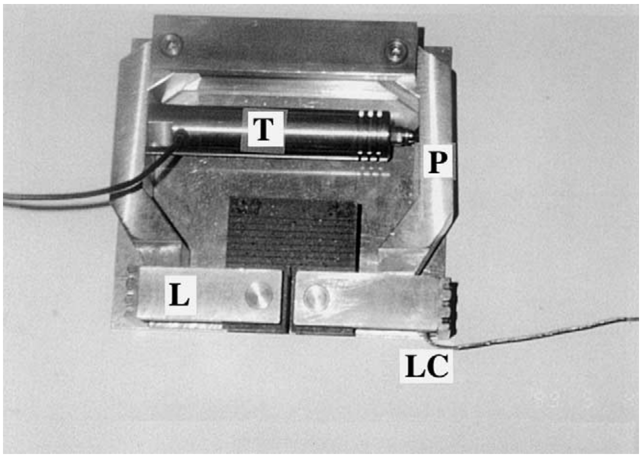

Fig. 4. Loading fixture used for in situ crack propagation study with a piezoelectric transducer T, which, after being activated by a high voltage amplifier, delivers an opening force via the pivot arms P and the loading arms L to the compact tension specimen. The load cell LC is located in one of the loading arms.

detail in [9]. It uses a piezoelectric transducer for load transfer. The piezoelectric transducer is placed between two pivot arms and delivers opening forces to the compact tension specimen through the loading arms. All parts are made of steel. The loading fixture allows testing to be performed under displacement control. A load cell is placed in one of the loading arms and monitors the applied load up to 3000 N. The piezo has a maximum displacement of 45 μm, however, the actual displacement is increased to 135 μm by the relative location of the loading pins and the piezo from the rotating hinge. This value can be increased further by prestressing the specimen with screws that link the piezo to the pivot arms.

Crack propagation measurements were performed in a controlled room-air environment (22°C, 50% relative humidity). The loading fixture was staged under an optical microscope. The microscope is equipped with a video camera connected to a TV screen and video recorder. The optical microscope has the advantage that wet specimens can be viewed. The crack propagation is continuously monitored and recorded on video. The magnification (400×) was sufficient to observe fiber bridging sites in the crack wake in these composites. A clip gage was mounted on the specimen to monitor the crack mouth opening displacement (CMOD). The incremental load is applied to the specimen by increasing the input voltage, which was computer controlled, to the piezoelectric transducer. Five specimens were tested of the IFC and the control, respectively. All specimens were loaded continuously up to failure. A slow displacement rate of 1 μm/s was chosen for all specimens to be able to observe the crack front and crack wake processes while loading.

4. Results and discussion

A typical load versus CMOD curve for unreinforced mortar and 0.2 vol% IFC composite is shown in Fig. 5. Both the ultimate strength and the tensile strain capability at ultimate strength are enhanced in the IFC composite compared to the control specimen. Of the five specimens tested, the strength enhancement ranges from 55% to 65% over the control specimens.

The in situ crack propagation measurements reveal that crack extension and propagation occurs in a stable but discontinuous fashion up to peak load. The crack propagation in the interground fiber composites is accompanied by a number of secondary microcracks. Secondary microcracks form either where the matrix strain is highest or the matrix is weakest. Fig. 6 taken during the strain hardening regime at 84% of peak load reveals the formation of stable secondary microcracks ahead of the crack tip. Once a secondary crack initiated it was bridged by fibers at onset due to the homogeneous fiber distribution. The fibers successfully shield the crack tip from the applied stress causing the microcrack to arrest. With increasing applied load levels, additional microcracks formed in adjacent regions. Eventually, one of these microcracks dominated and linked up with the primary crack. This type of stable, multiple secondary microcracking was not observed in microsteel fiber reinforced composites [10] due to their inhomogeneous fiber distribution.

At and beyond peak load, the crack growth is considered unstable because the crack propagates initially under constant, then decreasing load. To observe bridging sites after the peak load, the load was reduced which successfully arrested crack growth. Fiber pullout was the dominant toughening mechanism during the strain softening regime for fibers oriented perpendicular

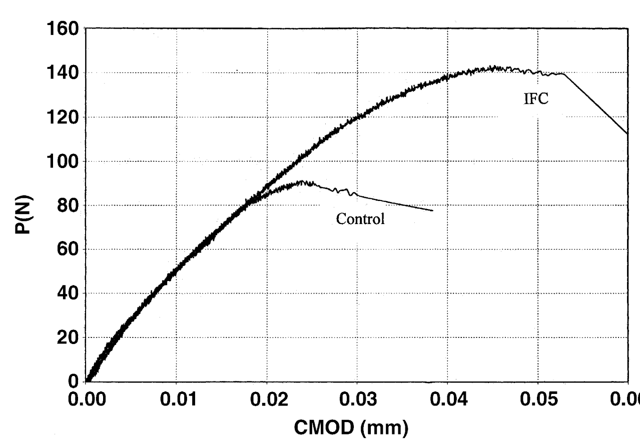

Fig. 5. Load versus crack mouth opening displacement (CMOD) curve for the control specimen (sieved IFC) and IFC composites with 0.2 vol% of polypropylene microfibers.

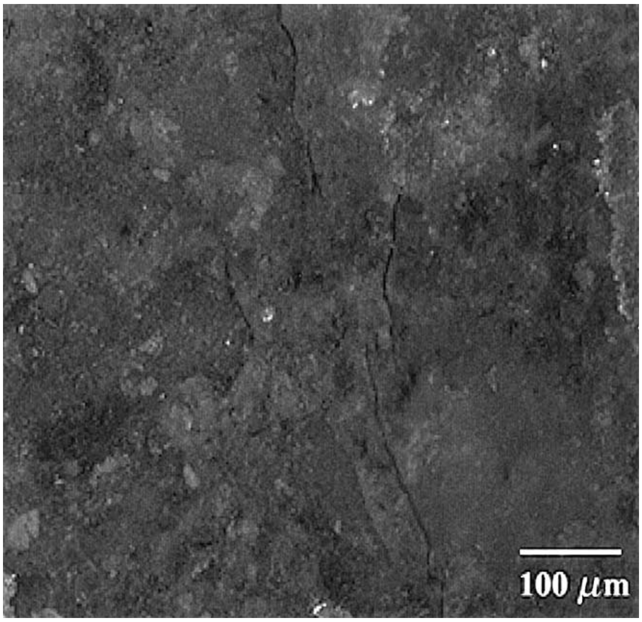

Fig. 6. Secondary microcracks that form during the strain hardening regime in IFC composites.

and slightly inclined to the propagating crack as shown in Fig. 7. Fig. 7(a), taken at peak load, the crack surfaces are bridged by a PP fiber. After failure of the specimen, the PP fiber pulled out of the matrix as shown in Fig 7(b). The observed fiber pullout length corresponds to the distance from the initial crack to the end of the fiber. When the fiber axis was strongly inclined to the propagating crack, fiber pullout was preceded by secondary microcrack formations along fiber/matrix interfaces as shown in Fig. 8. Figs. 8(a)–(c) were taken before, at peak load and at failure load, respectively. The initial crack that interacts with the partly embedded PP fiber in the center propagates from the top to the bottom of the micrograph. In Fig. 8(c), interfacial failure modes preceding fiber pullout are evident. Secondary microcracks form along the fiber/matrix interface contributing to the energy absorbing mechanisms in the strain softening regime. In contrast to Fig. 7(b), the initial crack in Figs. 8(a) and (b) does not remain the dominant crack. One of the microcracks that formed to the left of the initial crack became the dominant crack (Fig. 8(c)). Multiple secondary microcracks along the fiber/matrix interface are governed by high interfacial shear stresses. High interfacial shear stresses may be associated with the increased off axis orientation of the fibers in combination with the fiber surface modifications due to the milling process.

5. Conclusion

The interground fiber cement process allows lower fiber volume fractions to be utilized for strength enhancement. The milling process increases the roughness of the fiber surface and impregnates cement grains into the fiber surface. The impregnated cement grains increase the bond between the fibers and the matrix. The roughness of the fiber surface enhances the interfacial frictional shear stress. Both effects lead to strength

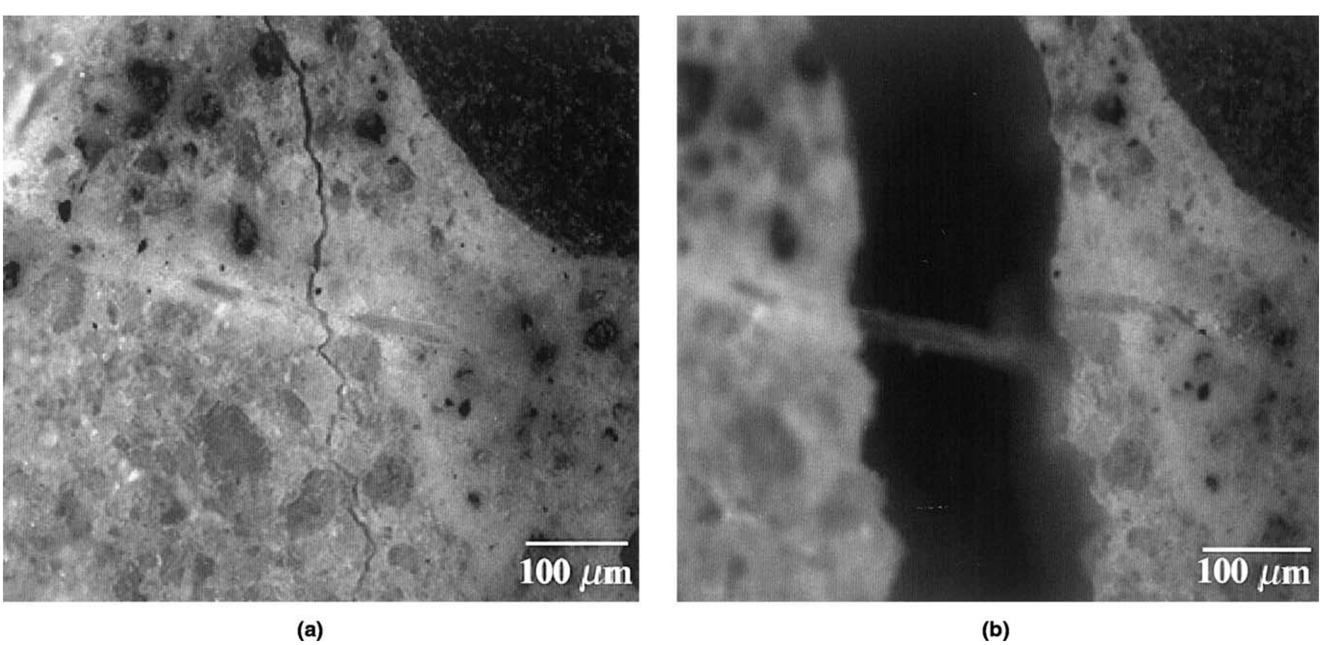

Fig. 7. Crack/fiber interaction in IFC for fibers slightly inclined to the propagating crack: (a) fiber bridging the crack surfaces at peak load; (b) micrograph taken after failure, revealing fiber pullout.

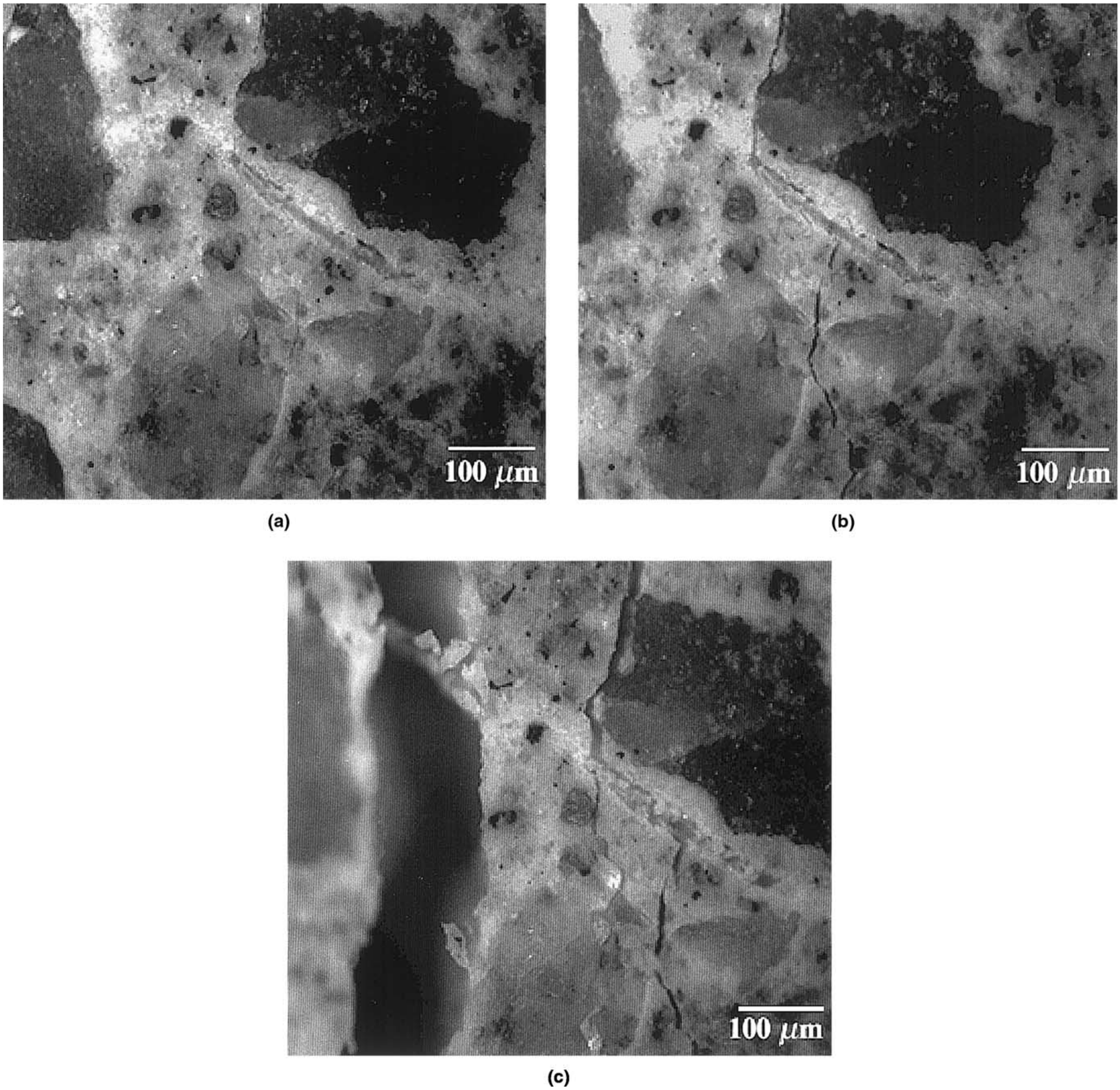

Fig. 8. Crack/fiber interaction in IFC of an inclined fiber: (a) before peak load; (b) at peak load, and (c) after failure. Fiber pullout was preceded by multiple secondary microcracks along the fiber/matrix interface in the strain softening regime.

enhancement. The homogeneous fiber distribution stabilizes crack growth and leads to formation of multiple secondary microcracks. The stabilized microcracks enhance the extensibility of the composite in the strain hardening regime. The dominant mechanism during the strain softening regime was fiber pullout. With increasing inclination of the fiber axis from the propagating crack, pullout was preceded by secondary microcrack formations along the fiber/matrix interfaces.

The economic advantage of IFC where strength enhancement can be achieved even at a fiber volume as low as 0.2% allows for a broader commercial use of cement based materials.

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