CARBON AND STEEL MICROFIBER-REINFORCED CEMENT-BASED COMPOSITES FOR THIN REPAIRS

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ABSTRACT: An experimental investigation was carried out to determine the suitability of fiber-reinforced cementitious composites containing high-volume fractions of very fine (micro) fibers of carbon and steel for thin repairs. Two series of tests were performed: the first in which the fracture characteristics of the fiber-reinforced composites themselves were assessed, and the second in which the bond developed between an old concrete substrate and fiber-reinforced repair composite was determined by conducting tensile tests on cylindrical repair assemblies. Tests were conducted at 22°C and at −50°C in an environmental chamber. The fracture characteristic of cement matrices were considerably improved due to microfiber reinforcement. Significant improvements in the repair bond strength value due to fibers were also noted. The test data clearly demonstrate the potential of microfiber-reinforced cement-based composites as a thin repair material.

INTRODUCTION

Repair and rehabilitation of our crumbling infrastructure has been generally recognized as one of the major challenges facing the construction industry today. There is a strong need to devise new and innovative techniques of executing repairs that would last longer and yet be economically feasible. The major reasons often cited for debonding and spalling of repairs are differential thermal movements, elastic incompatibilities, shrinkage stresses, occasional impact, rebar corrosion, substrate deficiencies, frost action, and poor workmanship (Felt 1956, 1960; *Guide* 1980; Ramey et al. 1988). Given these reasons for spalling and debonding of repairs, durable thin repairs (less than 25 mm thick) are particularly difficult to achieve.

For a durable repair, the desired characteristics of the repair material include low permeability, a high tensile strength, adequate impact resistance, sufficient deformability (ductility), high fracture toughness, low shrinkage, good dimensional stability, good abrasion resistance, and most of all, a strong tensile and shear bond with the base concrete. Reinforcement of cement-based materials with metallic, synthetic, and natural fibers has produced composites with much of the preceding desired characteristics for a repair material (Razl 1991). For thin repairs, however, the maximum dimensions of both the aggregate particles and the fibers have to be limited. Consequently, for thin repairs, the use of cements and mortars reinforced with very fine fibers (often called "microfibers") is conceivable.

Microfibers are fine fibers with lengths less than 10 mm and diameters less than 25 μm. With their high specific surface areas (>200 cm^2/g), they provide a large number of fibers in a given section of the composites and thus furnish more effective reinforcing mechanisms at the microcracking

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level. The result is that while the large "macrofibers" provide essentially no tensile strengthening at permissible volume fractions (Shah and Rangan 1971; Banthia et al. 1987) microfibers provide tensile strengthening as well as toughening of the host matrix (Banthia and Sheng 1990; Ouyang and Shah 1992). Some other improvements reported for the more researched carbon-microfiber–reinforced composites are: desirable shrinkage characteristics, improved dimensional stability; better durability; improved impact resistance; and enhanced deformability under biaxial bending (Banthia 1991; Ohama 1985; Banthia and Ohama 1989).

Since the microfiber-reinforced cementitious composites have the material performance characteristics desired for an effective repair, it was undertaken in the present study to investigate the bond these composites develop with the base concrete. Although several techniques of evaluating the bond strength exist (Ohama et al. 1986), a direct tensile bond test was chosen for the reasons of simplicity. Recognizing the fact that both strength and deformability of cementitious materials are sensitive to the environ-

TABLE 1. Properties of Microfibers

Fiber (1)	Length (mm) (2)	Diameter (μm) (3)	Specific gravity (4)	Tensile strength (MPa) (5)	Modulus of elasticity (GPa) (6)
Carbon	6	18	1.65	590	30
Steel	3 (avg.)	≈25 (avg.)	7.85	>600	200

FIG. 1. Section of Hydrated Cement Composite Reinforced with Carbon Fiber

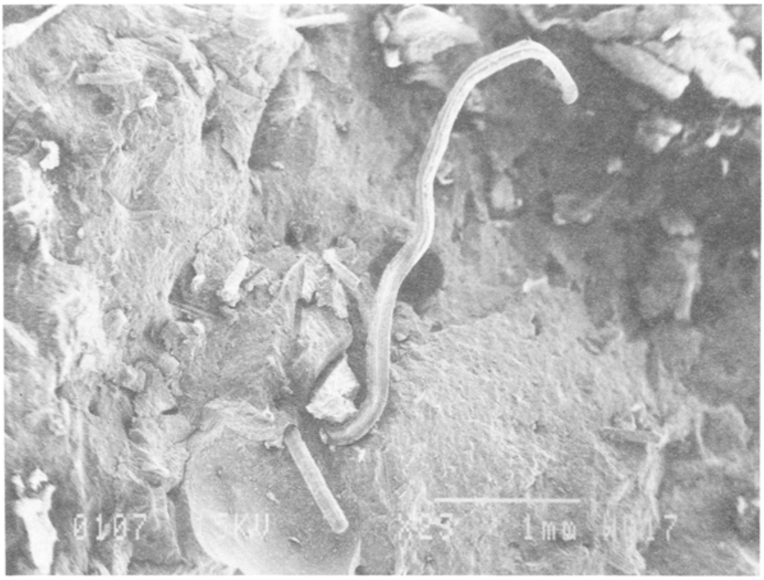

FIG. 2. Section of Hydrated Cement Composite Reinforced with Steel Microfiber

mental temperature, tests were conducted at both room and subzero temperatures.

EXPERIMENTS

Two series of tests were performed. In the first series, the fracture characteristics of fiber-reinforced composites themselves were evaluated, and in the second series, the tensile bond strengths developed between these composites and an ordinary base concrete were determined. Tests were performed at room temperature, and then repeated at a low temperature of −50°C.

Microfibers of carbon and steel with properties given in Table 1 were investigated. Carbon fibers employed were commercially available pitch-based fibers, whereas the steel fibers were experimentally produced by shaving mild steel. While carbon fibers were uniform in dimensions and section, steel fibers were not. Both cement paste and mortar matrices were reinforced with these fibers to produce the repair composites. ASTM type I cement was used throughout. In the cement paste matrix, the proportions by weight were 1.0:0.35:0.20 (cement:water:silica fume). The corresponding weight proportions for the mortar matrix were 1.0:0.35:0.50:0.20 (cement:water:sand:silica fume). Paste matrices were reinforced at fiber dosages of 1%, 3%, and 5%, whereas mortar matrices were reinforced at fiber dosages of 1%, 2%, and 3% by volume. The sand used was normal river sand with a maximum particle size of 2.4 mm. As noted previously (Banthia and Sheng 1990; Ohama et al. 1985), silica fume was found to be a very effective fiber dispersant. The other advantage of adding silica fume was in an improved fiber-matrix bond. In all fibrous mixes, a relatively high dosage of superplasticizer (between 5 and 25 ml/kg of cement) was used. Plain mixes

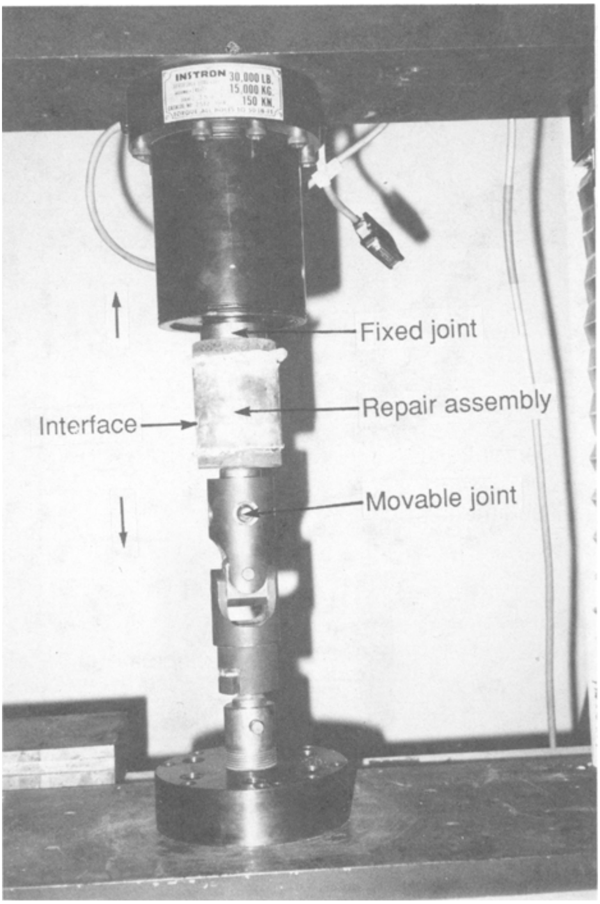

FIG. 3. Test Setup for Conducting Tensile Bond Tests on Repair Assemblies

without fibers contained a nominal dosage (3 ml/kg of cement) of superplasticizer. Figs. 1 and 2 show micrographs of hydrated fibrous composites. The base concrete used as substrate had the weight proportions of 1.0:0.35:0.85:1.56 (cement:water:fine aggregate:coarse aggregate). Superplasticizer at a dosage of 5 ml/kg of cement was added. The concrete had 12.5 mm maximum size coarse aggregate and had developed a compressive strength of 35 MPa when tested according to ASTM C39-86 at an age of 28 days.

To evaluate the tensile bond developed between the repair composites and the base concrete, cylindrical composite specimens (65 mm) were used. A 15–20 mm thick coating of the repair composite was laid on a 45–50 mm thick 14 day moist-cured base concrete cylinder without the use of any intermediate bonding agent. Natural surface finish of base concrete, cast in an externally vibrated form, was maintained without any surface treatment. Six specimens were cast for each mix. The old concrete-new composite

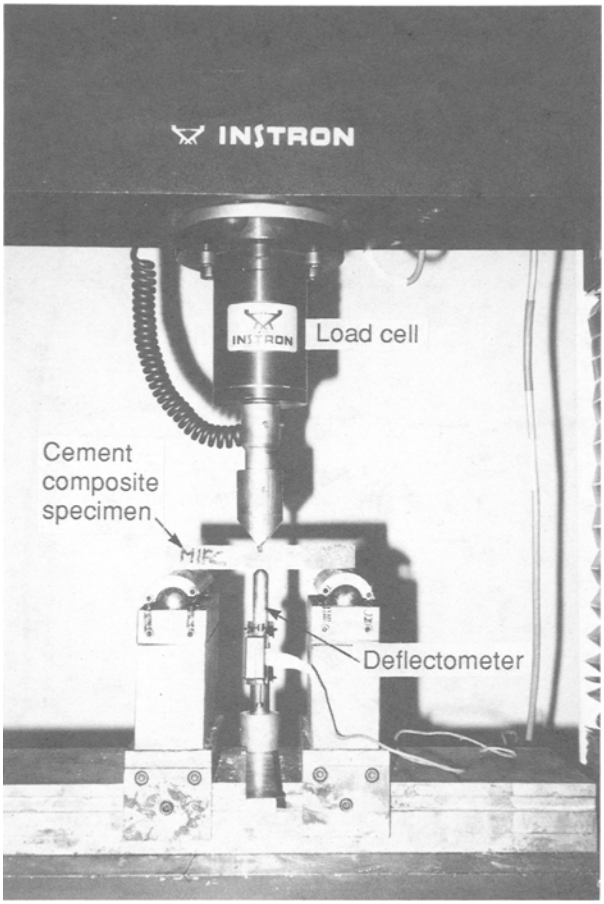

FIG. 4. Test Setup for Conducting Flexural Tests on Repair Composites

assembly thus produced was further cured for 14 days at 23°C ± 1°C under 95% relative humidity.

One day prior to the test date, two steel plates were epoxied to the top and bottom of the repair specimens to facilitate their attachment to the testing machine. On the day of the test, the specimens were attached to the frame of the testing machine through a fixed-movable connection as shown in Fig. 3. Preliminary testing indicated that a fixed-movable connection, as compared to movable-movable or fixed-fixed arrangements, led to reduced variations in the results, presumably due to reduced eccentricities. Repair specimens were subjected to tensile loads applied at a cross-arm displacement rate of 2 mm/min and the peak loads were recorded.

In the companion test series, the fracture characteristics of the fiber-reinforced repair composites themselves were evaluated by conducting flexural tests. Prismatic specimens 19 mm × 19 mm × 150 mm were tested on an unsupported span of 130 mm under three-point flexure with a cross-arm

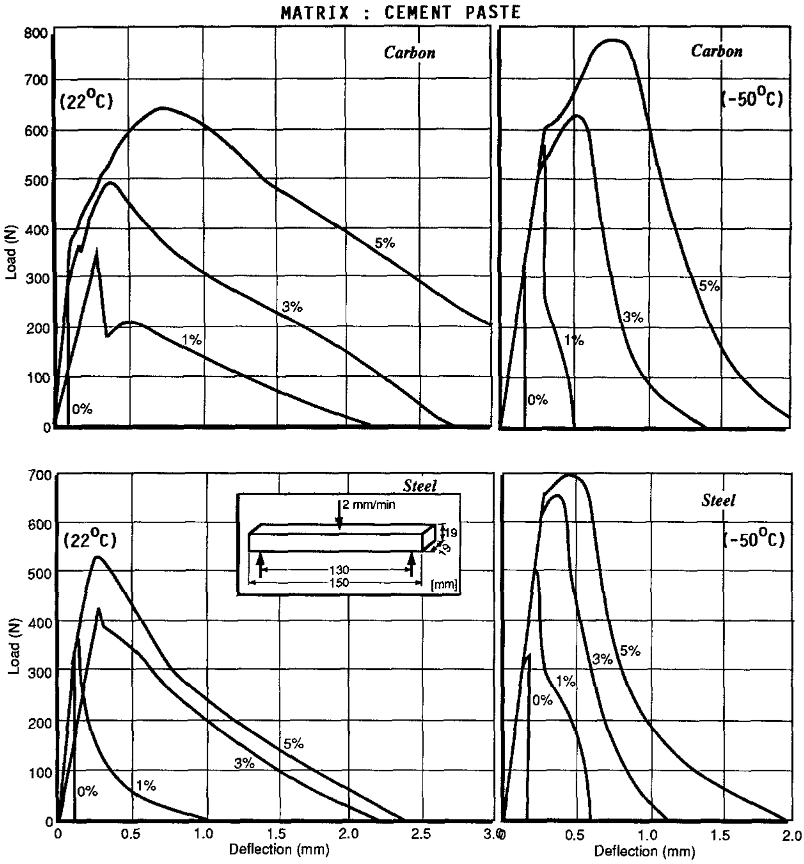

FIG. 5. Representative Load-Deflection Plots for Fiber-Reinforced Pastes at 22°C and −50°C

displacement rate of 2 mm/min. The test setup is shown in Fig. 4. Applied load versus beam midpoint displacement plots were obtained.

Both the series of tests were conducted at 22°C and then repeated at −50°C in an environmental chamber using liquid nitrogen.

RESULTS AND COMMENT

Fracture Characteristics of Fiber-Reinforced Repair Composites

The representative load-displacement plots for pastes and mortars reinforced with microfibers are shown in Figs. 5 and 6, respectively. The fracture behavior of microfiber-reinforced composites, in general, followed the trends reported previously (Banthia and Sheng 1990) and may be summarized as follows:

1. Microfibers brought about significant improvements in the fracture characteristic of the host matrix. Among the two microfibers investigated,

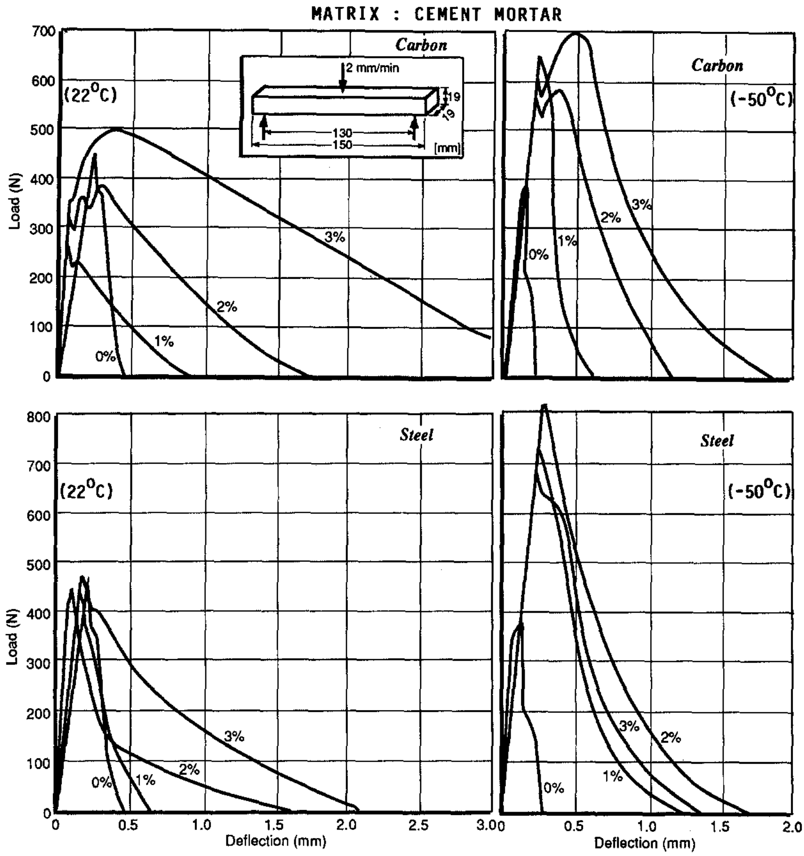

FIG. 6. Representative Load-Deflection Plots for Fiber-Reinforced Mortars at 22°C and −50°C

more effective strengthening and toughening occurred due to carbon fibers as compared to steel fibers.

2. At a low temperature of −50°C, fibrous composites are stronger but more brittle than at a temperature of 22°C.

3. In general, the peak loads in the case of carbon fiber-reinforced composites occur at greater displacements than those for composites containing steel fibers.

Tensile Bond Developed between Base Concrete and Repair Composites

During the tensile bond tests (Fig. 3), three failure modes could be recognized: failure at the interface (adhesion failure), failure in the material (cohesion failure), and failure at the grip. Irrespective of the failure mode, the peak load recorded in a given test was divided by the specimen cross-sectional area to obtain a quantity termed "apparent repair bond strength." Figs. 7 and 8 show the apparent repair bond strengths developed between the repair composites and the base concrete at 22°C and −50°C, respec-

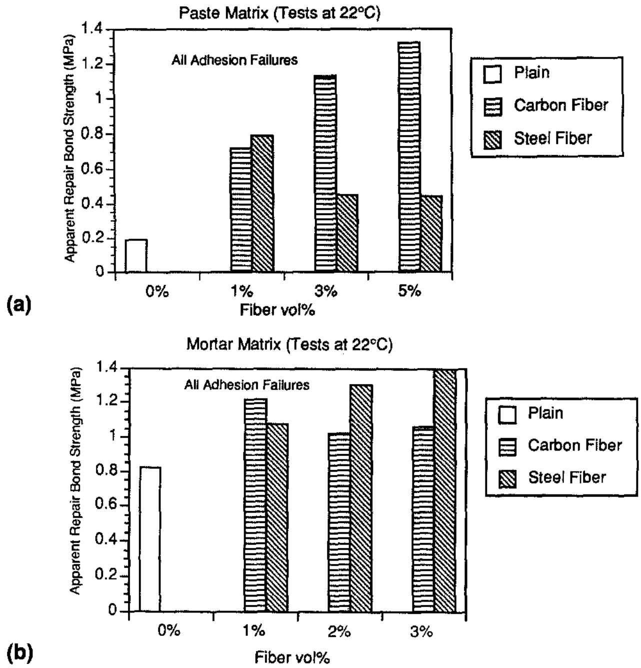

FIG. 7. Average Apparent Repair Bond Strength Value at 22°C

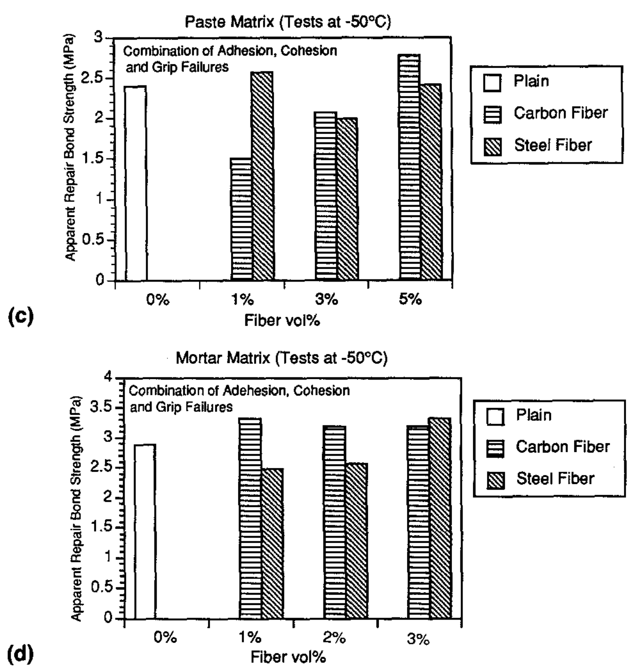

FIG. 8. Average Apparent Repair Bond Strength Value at −50°C

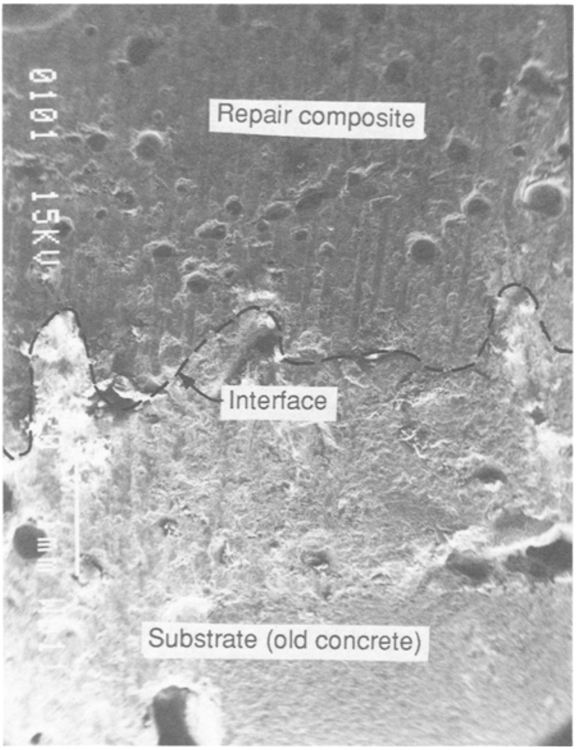

FIG. 9. Micrograph Showing Composite-Substrate Interface (Note Tortuous Nature of Interface)

tively. The repair bond strength values in Figs. 7 and 8 are averages of six specimens with a coefficient of variation of less than 15%. Notice that while interface (adhesion) failures occurred in all of the tests at 22°C, failures in the material and at the grip also occurred at −50°C.

At a normal temperature of 22°C with all failures occurring at the interface, the improvement in the apparent repair bond strength due to fiber addition may be noticed. For the tests conducted at −50°C, although the apparent repair bond strengths are considerably improved as compared to 22°C, no particular influence of the fibers became apparent. It is probable that because of the failures in the material as well as at the grip at −50°C, any possible improvements due to fiber addition stayed obscured.

A discussion of the possible mechanisms that cause strengthening of repair bond in the presence of fibers is as follows. Shrinkage cracking must exist at all repair interfaces due to differential shrinkage between the hardened substrate and the freshly laid plastic overlay. These flaws, under an applied tensile load, must cause stress concentrations and render the interface tension-weak. It is because of this phenomenon that the interfacial bond strength values observed for repairs executed with plain paste (Fig. 7) were significantly lower than those with plain mortar; significantly pronounced shrinkage cracking may be expected to occur at the repair interface in the case

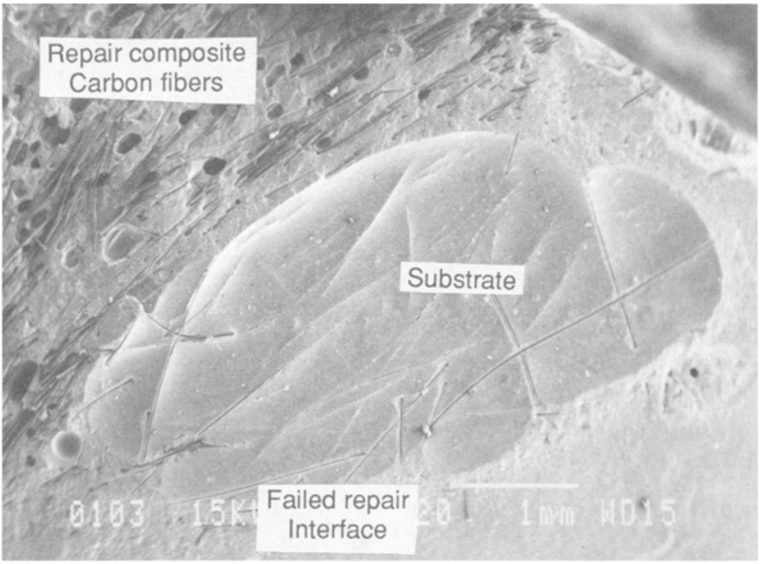

FIG. 10. Plan View of Fractured Repair Interface after Test Showing Part of Carbon-Cement Composite Remaining Bonded to Substrate

of plain paste. Fibers, in this regard, may be expected to cause an overall reduction in the shrinkage related cracking at the interface and to distribute the cracks more uniformly by arresting, blunting, deflecting, and branching these cracks. With a reduction in the sizes of the flaws at the interface, the repair assembly can support a higher tensile load.

The improvement in the interfacial bond strength due to fibers, when in fact the fibers are not expected to cross the interface, is arguable. However, as seen from Fig. 9, the repair composites filled the substrate irregularities and the failure planes usually traversed the composite and rarely the true composite-substrate interface, which is notably tortuous. Examinations of the failed interfaces (Figs. 10 and 11) revealed that even when the repair assemblies seemingly failed at the interface, a portion of the fibrous repair composite stayed bonded with the substrate. With cracks propagating in the composite, one can estimate the composite fracture properties to be of a direct relevance in these bond tests. Although the deflections were not recorded in these tests, it is possible that the peak loads in the case of specimens containing fibers occurred at greater deformations than those without.

Finally, the observed increases in the tensile bond strength may be related to the role of the superplasticizer itself. Notice that for the fibrous mixes, greater quantities of superplasticizer were used. Conceivably, this led to an exiguous packing of hydration products at the interface in the case of mixes containing no fibers and thus reduced the bond.

The values of tensile bond strength depend upon the surface texture and characteristics of the substrate, and in the present work, only a naturally vibrated surface was investigated. Realistic surfaces like sawn-cut, chisel-

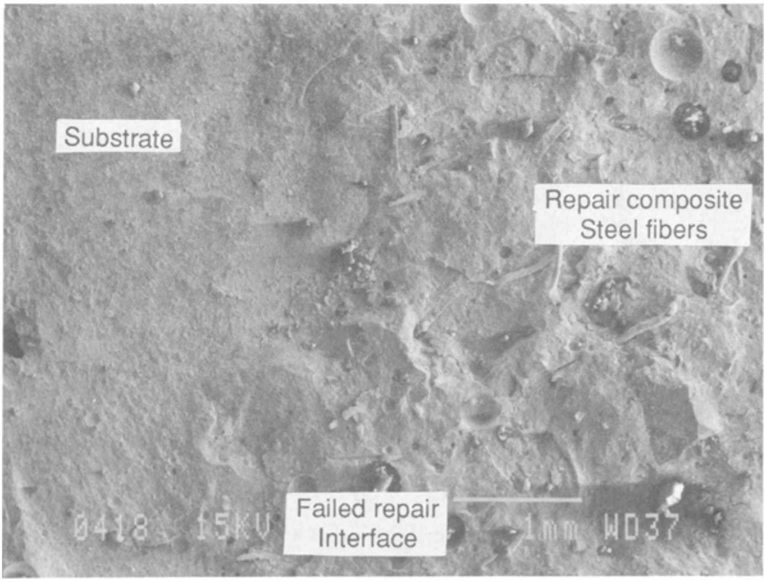

FIG. 11. Plan View of Fractured Repair Interface after Test Similar to Carbon-Fiber Composite (Fig. 10), Showing Part of Steel Microfiber-Reinforced Repair Composite also Remaining Bonded to Substrate

hammered, sand-blasted, or high-pressure-water-cleaned should be considered. Future work with more realistic site conditions is currently under way.

CONCLUDING REMARKS

Improvements in the tensile bond strength may be obtained by reinforcing-cement–based repair materials with microfibers of carbon and steel. At very low temperatures, while the repair bond strengths were considerably higher than those at normal temperatures, no particular influence of the fibers became apparent.

The laboratory evidence provided in the present paper of improvements in the repair bond strength due to fibers, is encouraging. The practical use of these composites, however, remains to be investigated.

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