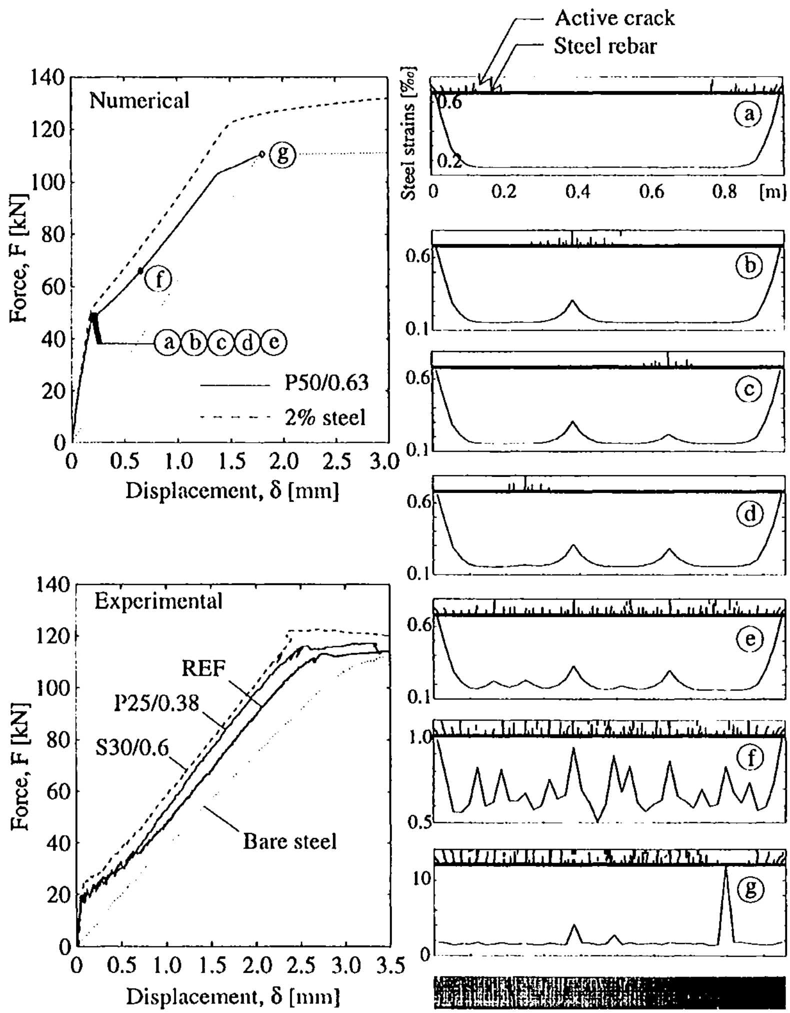

Fig. 9—Results of experiments and FE-analysis for tie elements.

SP 182-8

Bond of Deformed Bars to Concrete: Effects of Specialty Cellulose Fibers

by P. Soroushian and S. Ravanbakhsh

Processed cellulose fibers provide high levels of elastic modulus, tensile strength, bond strength to concrete, and durability. Their fine diameter also yields a close fiber spacing at relatively low fiber volume fractions, and allows them establish a strong presence in the interface zones between reinforcing bars and concrete. Specialty cellulose fibers have been recently developed for convenient dispersion into normal concrete mixtures using conventional mixing procedures. This research project investigated the effect of specialty cellulose fibers at volume fractions of about 0.1% on the strength and toughness of bond between deformed bars and concrete. The experimental results were indicative of the effectiveness of specialty cellulose fibers in enhancing bond strength and toughness. The positive impact of specialty cellulose fibers on bond strength was more pronounced as fiber volume fractions increased to the upper limit of 0.18% considered in this investigation.

Keywords: bond; cellulose fibers; concrete; deformed bars; pull-out; strength; toughness

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INTRODUCTION

The structural performance of reinforced concrete partly depends on the bond strength and bond stress-slip behavior at the interfaces between reinforcing bars and concrete. Deformed surfaces of reinforcing bars cause various local and global damage mechanisms when they are pulled against the surrounding concrete. Fine discrete fibers which are closely spaced in the close vicinity of reinforcing bars in concrete would be expected to enhance the performance of concrete under these local and global damaging effects and thus benefit the bond strength and toughness of concrete. The work reported herein determines the effects of specialty cellulose fibers on the bond behavior of deformed bars in concrete.

RESEARCH SIGNIFICANCE

Bond of deformed bars to concrete is critical to various aspects of reinforced concrete behavior, including flexural strength, toughness, and seismic resistance. Improvement of the bond behavior with low volume fractions of specialty cellulose fibers would thus have important implications for structural applications of fiber reinforced concrete.

NATURE OF BOND BEHAVIOR

The bond resistance between deformed bars and concrete is provided by a combination of chemical adhesion, friction, and interlocking (Figure la).(1) Once the adhesion of steel surfaces to concrete is lost, friction and most importantly interlocking govern the bond behavior. The bar deformations interlocked within concrete apply bearing pressures to concrete at an inclined direction (Figure lb). This generates local damage in the form of cracks initiating from the bar deformations. The inclined nature of these bearing pressures also produces an internal radial pressure against concrete (Figure lc), which leads to the generation of splitting tensile cracks (Figure 1d). Heavy confinement of concrete around bars as well as large concrete cover thicknesses tend to promote failure by increasing local damage (Figure lc).

Low confinement levels and small cover thicknesses, on the other hand, promote more brittle failure modes associated with the formation of splitting cracks (Figure 1d).

SPECIALTY CELLULOSE FIBERS

Processed cellulose fibers have found growing applications in thin reinforced cement products.(2) These applications have confirmed the high reinforcement efficiency and durability of processed cellulose fibers in cement-based materials. Conventional cellulose fiber reinforced cement composites are produced using special prefabrication techniques where excess moisture and mechanical efforts are used to ensure uniform dispersion of fibers in the matrix. Recently, specialty cellulose (fabroset™) fibers have been developed which are readily dispersible in conventional concrete and mortar mixtures using normal mixing procedures. These fibers can be added to the mix at any stage, including after the addition of other mix ingredients, and the simple mixing action used with concrete would be sufficient to uniformly disperse the fibers in concrete.

Table 1 compares some key attributes of the specialty cellulose fibers with those of commercially available polypropylene fibers. Specialty cellulose fibers are distinguished by their high elastic modulus and bond strength, and small diameter (i.e. high surface area). The hydrophilic surface of specialty cellulose fibers facilitates their dispersion in concrete and enhances the interface characteristics. It should be noted that the effective diameter of specialty cellulose fibers is not much greater than the particle size of cement; this minimizes any disturbance of the packing of cement particles and the distribution of cement hydration products resulting from the presence of fibers, and thus enhances the bulk properties of the matrix. Fiber densities less than that of water (1 g/cm^3 or 62 lb/ft^3) encourage segregation due to floating, the density of specialty cellulose fibers (1.5 g/cm^3 or 93 lb/ft^3) thus favors their case in concrete. The specialty cellulose fibers used in this project are highly durable in the alkaline environment of concrete; their effect on fresh mix slump is comparable to that of polypropylene fibers.

In fiber reinforced concrete it is essential to achieve close fiber spacings, high fiber count, and large fiber surface area. Polypropylene fibers at about 1.2 kg/m^3 (2 lb/yd^3) are commonly used as secondary reinforcement in concrete. This dosage is equivalent to 0.133% fiber volume fraction. An equal weight dosage of cellulose fibers, given the higher specific gravity of these fibers, accounts for 0.08% fiber volume fraction. Table 2 compares the fiber spacings, fiber counts and fiber surface areas achieved through the addition of 1.2 kg/m^3 (2 1b/yd^3) of cellulose and polypropylene fibers to concrete. The smaller diameter of cellulose fibers clearly benefits these key measures of reinforcement efficiency in concrete.

REINFORCING ACTION OF SPECIALTY CELLULOSE FIBERS

Specialty cellulose fibers enhance the properties of concrete through interfering with the processes of microcrack propagation and cracking in concrete. With a modulus of elasticity that is higher than that of concrete, the closely spaced specialty cellulose fibers with strong bonding to concrete resist the concentration of strains near crack tips (Figure 2a) and also at the edge of bar deformations (Figure 2b). This delay in crack formation and propagation is expected to increase the bond strength of deformed bars in concrete.

Specialty cellulose fibers with their close spacing, high surface area, and high tensile and bond strengths also force a tortuous path of crack propagation (Figure 2c) and resist widening of cracks by bridging across them (Figure 2d). Finally, the fineness of cellulose fibers allows them reinforce the mortar fraction of concrete which occupies the critical thin zone between bar deformations. These effects of specialty cellulose fibers are expected to provide for a ductile failure of the bond between deformed bars and concrete.

EXPERIMENTAL RESULTS WITH POLYPROPYLENE AND NYLON FIBERS

Bond properties of reinforcing bars embedded in polypropylene and nylon fiber reinforced concrete have been reported in References 3 and 4, respectively. In both cases, bars were pulled out from concrete cubes, and fiber volume fractions were below 0.2% (following the commercial practice). The results indicated that the addition of polypropylene and nylon fibers does not influence the bond strength or the bond stress-slip behavior of deformed bars in concrete.

EXPERIMENTAL PROGRAM

We subjected deformed reinforcing bars of Grade 60 with 414 MPa (60 ksi) yield strength and 19 mm (0.75 in) diameter to the pull-out test of ASTM C 234 (Figure 3). The concrete used in this project had a cement content of 332 kg/m^3 (560 lb/yd^3) and a water-to-cement ratio of 0.56. The coarse aggregate was crushed limestone with 25 mm (1 in) maximum particle size, and the fine aggregate was river sand. The mix was air-entrained with about 6% air content. This concrete had a slump of 150 mm (6 in), and its compressive and flexural strengths were 31 and 4 MPa (4.5 and 0.6 ksi), respectively. The pull-out tests were repeated with specialty cellulose fibers added to concrete at different dosages; the test program is presented in Table 3.

TEST RESULTS AND DISCUSSION

The deformed bars pulled out of plain and fiber reinforced concrete specimens without causing splitting cracks. Failure seemed to have initiated by the formation of inclined cracks as shown in Figure 1 c, and then continued by shearing off the concrete between bar deformations. Typical experimental bond stress-slip relationships resulting from pull-out tests are presented in Figure 4. Bond stress was obtained by dividing the pull-out load by the normal interface area between the bar and concrete. The average values of ultimate bond strength and toughness (defined as the total area under the bond stress-slip curve) are presented in Figure 5. These results indicate that low dosages of specialty cellulose fibers are effective in enhancing the strength and specially toughness of the bond between deformed bars and concrete.

The test results presented above support the hypothesis that the effectiveness of specialty cellulose fibers in the control of crack formation and propagation, resulting from their close spacing and high elastic modulus, tensile strength and bond strength to concrete, benefits the bond strength and toughness between deformed bars and concrete. This is true even at fiber volume fractions below 0.1%.

CONCLUSIONS

Specialty cellulose fibers, developed recently for convenient dispersion in normal concrete mixtures using conventional mixing procedures, are effective in enhancing the bond strength and toughness between deformed bars and concrete, even when added to concrete at volume fractions below 0.1%. At such low fiber volume fractions, fiber reinforced concrete offers fresh mix workability characteristics which are comparable to those of plain concrete; the cost implications of using such low fiber contents in concrete are also limited. The effects of specialty cellulose fibers on bond strength and toughness were more pronounced as the fiber volume fraction was increased to the upper value of 0.18% considered in this investigation. At such low fiber volume fractions, polypropylene and nylon fibers have not caused any improvements in bond behavior in past investigations. Specialty cellulose fibers, offering relatively high elastic modulus, tensile strength and bond strength to concrete, with fine diameters and thus close fiber spacings in the vicinity of reinforcing bars, provide practical and economical means of enhancing the performance characteristics of reinforced as well as plain concrete.

ACKNOWLEDGMENT

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TABLE 1—FIBER CHARACTERISTICS.

PROPERTY	PREFERENCE	FIBER TYPE	
		SPECIALTY CELLULOSE	FIBRILATED POLYPROPYLENE
Elastic Modulus GPa (ksi)	High	60 (8,700)	4 (850)
Bond Strength MPa (ksi)	High	1.5 (0.20)	0.4 (0.06)
Tensile Strength MPa (ksi)	High	500 (72)	600 (87)
Effective Diameter μm (in)	Low	15 (0.0006)	60 (0.0024)
Aspect (length-to-diameter) Ratio	High	200	200
Hydrophilic/ Hydryphobic Surface	Hydrophilic	Hydrophilic	Hydrophilic
Density g/cm^3 (lb/ft^3)	Slightly greater than 1.0	1.5	0.9
Alkali Resistance	High	High	High

TABLE 2—VALUES OF FIBER SPACING, COUNT AND SURFACE AREA (ACI COMMITTEE 544, 1995).

PROPERTY	PREFERENCE	FIBER TYPE	
		SPECIALTY CELLULOSE	FIBRILATED POLYPROPYLENE
Fiber Spacing[1] mm (in)	Low	0.53 (0.021)	2.8 (0.11)
Fiber Count[2] 1/cm^3 (1/in^3)	High	90 (1,475)	0.5 (8)
Specific Surface Area[3] 1/cm (1/in)	High	0.13 (0.33)	0.033 (0.083)

[1] Spacing = $d_f/\sqrt{V_f}$, where d_f= fiber diameter, and V_f= fiber volume fraction
[2] Fiber Count = $0.077\ V_f / (\ell_f \cdot d_f^2)$, where ℓ_f = fiber length
[3] Specific Surface Area = $0.244\ V_f / d_f$

TABLE 3—THE EXPERIMENTAL PROGRAM.

Fiber Dosage kg/m^3 (lb/yd^3)	Equivalent Fiber Volume Fraction (%)	Number of Pull-Out Test Specimens
0	0	2
0.9 (1.5)	0.06	3
1.35 (2.25)	0.09	2
1.8 (3)	0.12	2
2.7 (4.5)	0.18	2

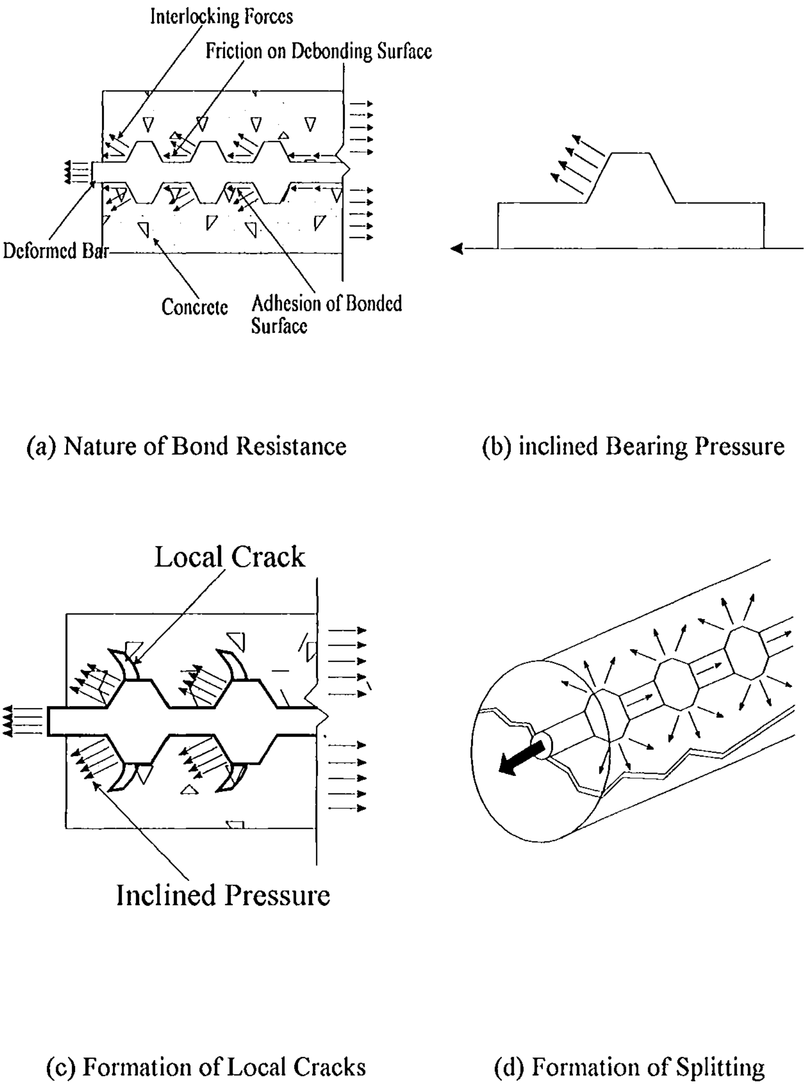
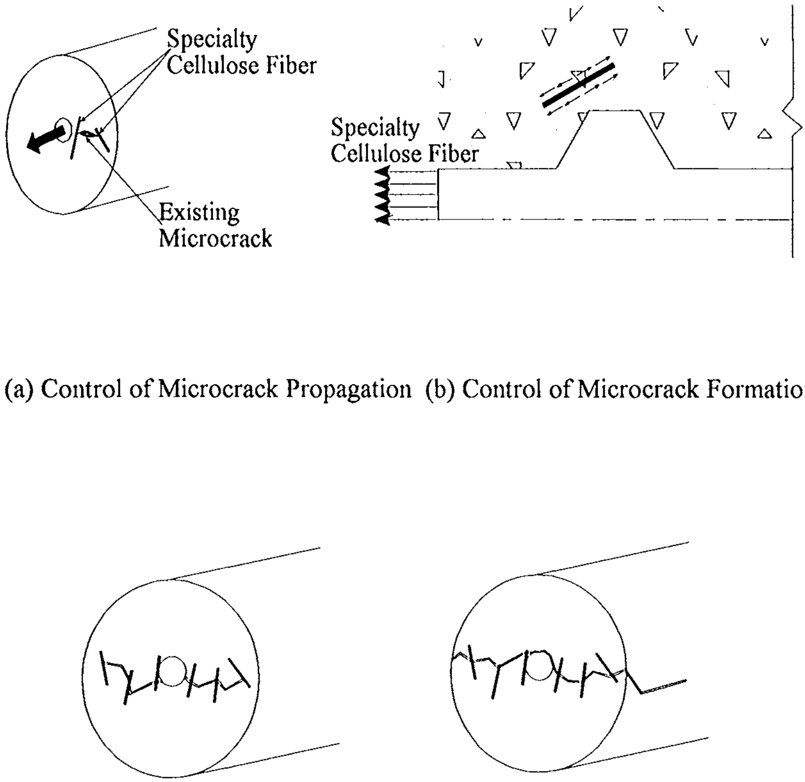


Fig. 1—The bond behavior of deformed bars in concrete.



(a) Control of Microcrack Propagation (b) Control of Microcrack Formation

(c) Tortuous Crack Path With Fibers (d) Bridging Action of Fibers

Fig. 2—Mechanisms of action of specialty cellulose fibers in concrete.