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Improving the interface bond between fiber mesh and cementitious matrix

B. Mu, C. Meyer*, S. Shimanovich

Department of Civil Engineering and Engineering Mechanics, Columbia University, New York, NY, 10027, USA

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Abstract

The use of continuous fiber mesh as reinforcement of cementitious composites is attractive for various applications. In this paper, fracture toughness was used to evaluate the flexural behavior of glass concrete reinforced with either AR-glass or polypropylene fiber mesh. AR-glass fiber mesh was found to be much more efficient, but polypropylene fiber mesh is less expensive and has no aging problem. A research project is underway at Columbia University to improve the bond between the polypropylene fiber mesh and cementitious matrix. Results obtained so far indicate a great improvement of the mechanical properties of the fiber mesh-reinforced material.

Keywords: Admixture; AR-glass; Bond strength; Fiber mesh; Polypropylene

1. Introduction

A major research effort has been underway at Columbia University to evaluate the use of waste glass as an aggregate for concrete [1,2]. One glass concrete product currently under development are thin sheets. These are most appropriately reinforced with continuous fiber mesh. Such mesh reinforcement is very effective in bridging cracks in the concrete matrix, which is an important factor for the durability of the material. This is an issue of highest priority in the civil engineering profession [3–5]. The design and controlled manufacture of continuous fiber mesh allow for a wide range of possibilities. It appears that target performance characteristics can be achieved more readily with continuous fiber mesh rather than with short randomly distributed fibers, especially when large fiber volume ratios are called for. This advantage is critical for thin sheet concrete products.

This paper reports on a study to identify an appropriate type of fiber mesh for thin sheet glass concrete products. Among the most promising materials were AR-glass and polypropylene. Flexural performance as measured in the toughness test according to ASTM C 1018 was used to evaluate and compare these two types of fiber mesh. It was found that AR-glass fiber mesh is much more efficient as reinforcement of glass concrete products than polypropylene fiber mesh, primarily because of its stronger and stiffer yarns. However, it is also about 10 times as expensive by weight or 30 times by volume.

Also, long-term weathering tests revealed that AR-glass fibers might exhibit tensile strength reduction and ductility loss with aging. They have been found to be quite stable in the alkaline environment of Portland cement-based matrices. However, strength reduction was experienced when AR-glass fiber-reinforced concrete was exposed to humid environments over long periods, together with a loss of ductility. Bentur and Diamond [6] studied the aging effect of AR-glass fiber-reinforced concrete with a crack advancing from a notch to intersect a perpendicular glass fiber strand. Composites with ductile behavior were characterized by the presence of unbroken filaments bridging the crack, with no hydration products found in the spaces between individual glass filaments within a strand. Composites that exhibited brittle behavior after aging were characterized by broken filaments due to the crack advance, with hydration products found between individual filaments. Although the mechanism of the aging problem is not clear, the loss in strength and ductility of AR-glass fiber-reinforced concrete in wet environments can be attributed mainly to physical factors [7], which cause the accumulation of calcium hydroxide in the spaces between and around the filaments. Because of the brittle properties of calcium hydroxide, this

* Corresponding author. Tel.:+1-212-854-3428; fax:+1-212-854-6267.
E-mail address: meyer@civil.columbia.edu (C. Meyer).

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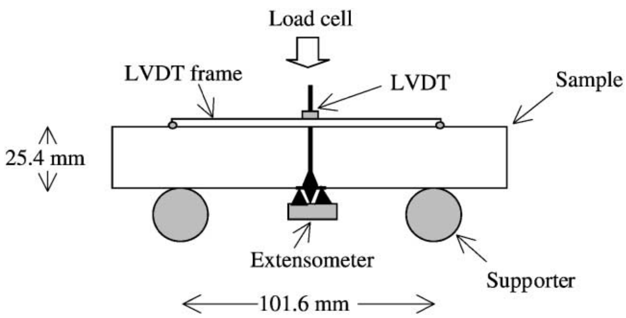

Fig. 1. Set-up of three-point bending test.

leads to increased bond and stress localization under loading and subsequently to embrittlement of AR-glass fiber-reinforced concrete [8].

The high cost of AR-glass fiber mesh and the potential aging problem provides incentives to improve the performance of polypropylene fiber mesh, for example, by enhancing its bond properties. The durability of fiber-reinforced cement composites was not subject of the present study.

In the work reported herein, the aging problem of AR-glass fibers was investigated by microhardness measurements. A special technology was developed to modify the bond between fiber and cement matrix. Fracture toughness test results are presented and compared for polypropylene fiber mesh-reinforced beams with and without the measures to improve the bond properties. Optical microscopy was employed to provide additional insight into how the bond modification affects the matrix microstructure.

2. Experiments

Microhardness along the AR-glass fiber–matrix interface was measured using a microhardness tester (MHT-4, Zeiss). Extruded thin plate specimens used in this test were made of (1) short alkali-resistant glass fibers (length = 12 mm, diameter = 8 μm), (2) type I Portland cement and (3) two kinds of silica sand (600–300 μm and 150–90 μm in diameter, obtained from David Ball). The water/binder ratio was 0.28. The plate specimens had a thickness of 6 mm and thus were suitable for an accelerated aging test. Two batches (Batches 0 and 0-1) were prepared. Batch 0-1 was cured normally (20 °C, RH > 90%), while Batch 0 was cured with low-pressure steam to simulate 1-year aging under 20 °C wet condition. According to the time–temperature equivalency, this condition is equivalent to accelerated aging of 1 day in wet storage at 80 °C.

The specimens for the flexural test were beams of dimensions 25.4 × 25.4 × 152.4 mm, tested in three-point bending over an effective span of 101.6 mm. Two types of fiber mesh were used: polypropylene fiber mesh with elastic modulus of 3.5 GPa and tensile strength of 620 MPa and AR-glass fiber mesh with elastic modulus of 70 GPa and tensile strength of 1800 MPa. Two different fiber volumes were considered for each type of fiber mesh. These are designated as V_f and $2V_f$, corresponding to one and two layers of fabric mesh, respectively, positioned on the tension side of the beam with 2-mm concrete cover. For polypropylene fibers, $V_f = 0.51\%$, while for glass fibers, $V_f = 0.19\%$. The polypropylene mesh had a 4.5 × 4.5-mm grid and the glass mesh had a 5 × 5-mm grid.

A single glass concrete mix design was used for all specimens. The water/binder ratio was 0.34. Approximately 15% of Type III cement was replaced by metakaolin to suppress the potentially harmful effects of ASR [2]. In addition, a superplasticizer was used to obtain the desired workability. During casting, intensive vibration was applied to assure complete penetration of the cement matrix through the fabric openings. All specimens were demolded after 1 day and thereafter placed in a moisture room for 25 days before being tested.

Flexural toughness tests according to ASTM C 1018 were conducted under closed-loop strain control on a 10-KN MTS-458 machine. A displacement transducer monitored the crack mouth opening and supplied the feedback signal to the servocontroller. A LVDT was mounted at the specimen center to record the net deflection (Fig. 1).

After the flexural test, the specimens were cut by a diamond saw and ground smoothly until the polypropylene fiber mesh was exposed. Specimens with two layers of fiber mesh were cut and ground such that the upper layer of fiber mesh could be removed and the lower layer exposed. Photographic images were taken and recorded by an optical microscope (CARL ZEISS) at a magnification of 10 ×.

3. Results and discussion

The relative microhardness values of AR-glass-reinforced specimens are plotted in Fig. 2 versus the distance from the fiber boundary. Relative values were obtained by dividing the measured microhardness values by the lowest value. The interfacial zones around short microfibers are

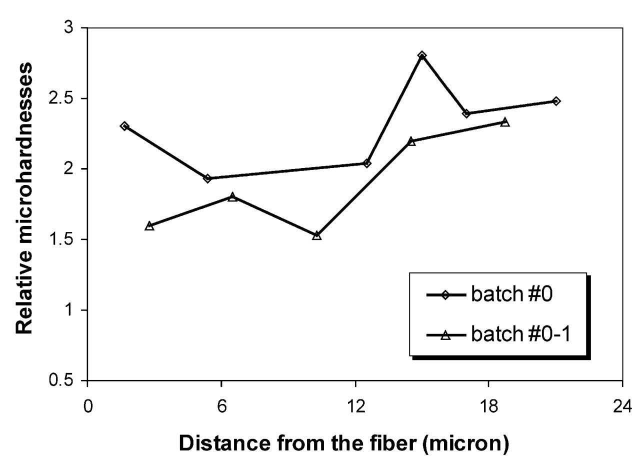

Fig. 2. Relative microhardnesses of AR-glass fiber-reinforced specimens.

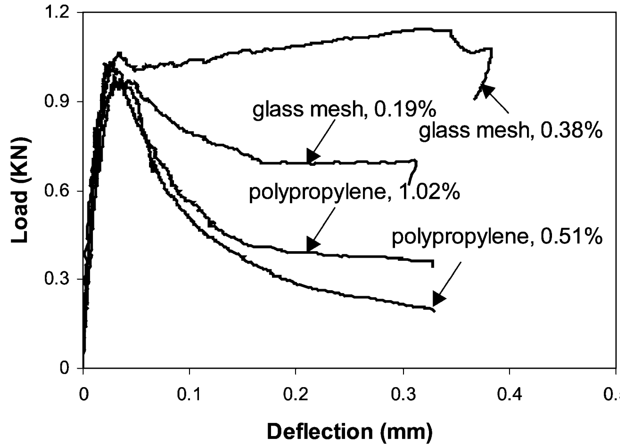

Fig. 3. Load–deflection curves for polypropylene and AR-glass mesh-reinforced samples (no bond modification).

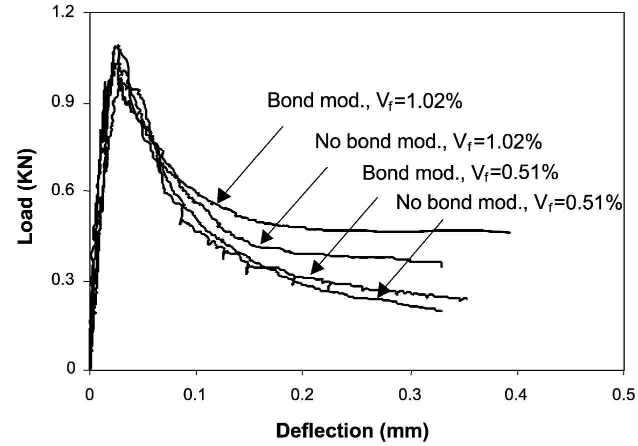

Fig. 4. Load–deflection curves for polypropylene mesh-reinforced samples with and without bond modification.

about 20 μm in width. The microhardness of the aged specimen (Batch 0) is clearly higher than that of the nonaged specimen (Batch 0-1), which indicates an increase in brittleness.

Fig. 3 gives the load–deflection curves of polypropylene and AR-glass mesh-reinforced specimens. Table 1 lists related test data. It can be seen that glass fiber mesh reinforcement is much more effective in increasing flexural toughness than polypropylene. Also, the first crack strength is higher, which improves durability, since fibers are better protected. The toughness indices of glass mesh-reinforced samples are up to 88% higher than those of polypropylene mesh-reinforced samples, while the volume ratio of glass mesh is only 37% of that of polypropylene mesh. This superior performance may be attributed mainly to the fact that glass fibers have a much higher tensile strength and elastic modulus. However, they are also much more expensive. Therefore, it was the objective of this work to improve the performance of polypropylene fiber mesh by modifying the interfacial zone between matrix and fiber mesh.

Fig. 4 gives the load–deflection curves of polypropylene mesh-reinforced specimens with and without the bond modification. The corresponding first crack strength and toughness indices are listed in Table 1. It can be seen that the bond modification improves the flexural performance, with the improvement being slightly more significant for specimens with two layers of fiber mesh at larger deflections. For the one-layer reinforced specimen, the latex increases the first crack strength by about 11%, while for the two-layer reinforced specimen, the increase is 6%. A possible explanation is that the latex increases the fluidity of the fresh cement composite. Thus, during vibration, the cement matrix becomes denser, improving the interfacial zone. Using the energy dissipation approach, Li et al. [9] determined that the first crack strength of cementitious composites is a function of matrix, interface and fiber properties. Since the elastic modulus of polypropylene mesh is lower than that of concrete, the first crack strength increase is mainly attributed to the improvement of the matrix, while the fiber mesh plays a less important role.

Whereas at small displacement the fibers appear to have a slightly negative effect on fracture toughness, at larger deflections, the beneficial effect of the bond modification becomes more apparent (Fig. 5). It smoothes the stress transition between fiber and matrix and reduces the stress concentration. The result is an increase in bending toughness.

Optical microscopic images show that batches with the bond modification have much denser microstructures than

Table 1
Test results for fiber mesh-reinforced samples

Fiber mesh material	V_f (%)	Modified bond	First crack strength (MPa)	Toughness indices I5	I10	I20
AR-glass	0.19	No	8.68	4.48	7.87	14.16
AR-glass	0.38	No	9.47	5.24	10.09	20.45
Polypropylene	0.51	No	8.58	3.96	6.83	9.56
Polypropylene	1.02	No	9.14	4.34	6.86	10.89
Polypropylene	0.51	Yes	9.55	3.83	7.51	9.82
Polypropylene	1.02	Yes	9.68	4.29	7.76	12.09

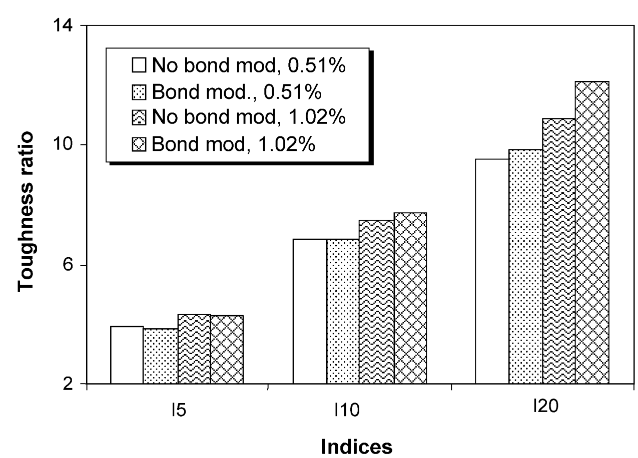

Fig. 5. Toughness indices for polypropylene mesh-reinforced samples with and without bond modification.

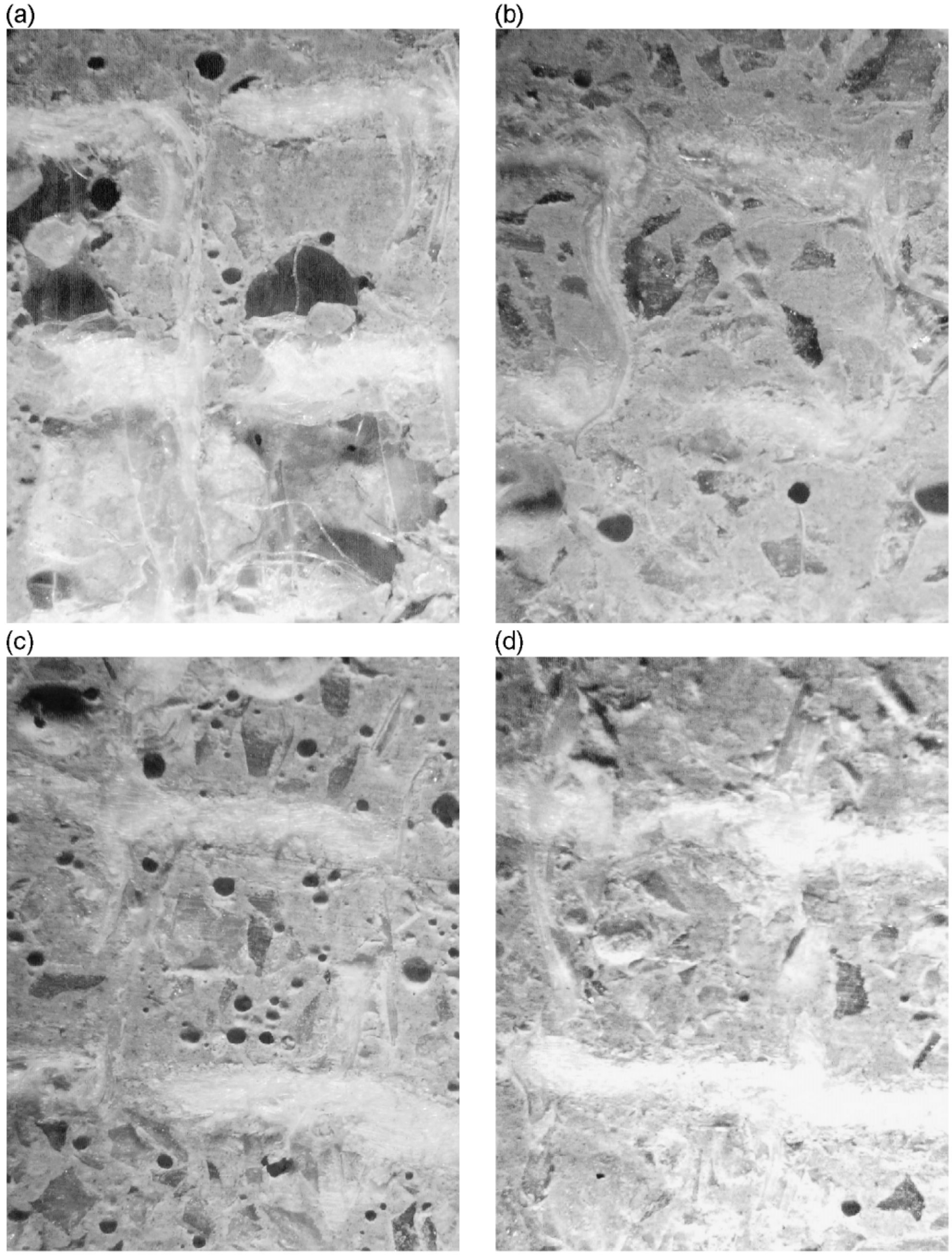

Fig. 6. Optical microscopic images of samples (magnification 10 ×). (a) 1.02% Polypropylene mesh, without bond modification. (b) 1.02% Polypropylene mesh, with bond modification. (c) 0.51% Polypropylene mesh, without bond modification. (d) 0.51% Polypropylene mesh, with bond modification.

those without (Fig. 6). As observed during casting, the batches with bond modification were highly fluid compared with those without at the same water/cementitious materials ratio. The higher fluidity eases the penetration of the fiber mesh and formation of a compact texture. Such penetrability is highly desirable for specimens with multiple layers of fiber mesh. A comparison of Fig. 6a and b reveals the improvement of the microstructure for specimens with two layers of mesh reinforcement. This improvement is probably responsible for the observed increase in strength and toughness indices.

4. Conclusions

The aging of the interface between the alkali-resistant glass fiber and cementitious matrix reduces the ductility and toughness of the specimens. From an economic point, polypropylene fiber mesh is a more desirable type of reinforcement for thin-sheet glass concrete products than glass fiber mesh. However, because of its lower tensile strength and elastic modulus, its reinforcing effect needs to be improved. A comparison of the reinforcing efficiency of polypropylene fiber mesh and AR-glass fiber mesh, based on a three-point bending test, found the cost/toughness ratio of AR-glass mesh to be around 6.4 times as high as that of polypropylene mesh. By modifying the bond between fiber and cementitious matrix, the flexural behavior of polypropylene mesh-reinforced samples is improved. The first crack strengths are even higher than those of glass mesh-reinforced samples. This should be attributed to the improvement of matrix and interfacial zone between fiber and matrix due to the high fluidity of fresh cementitious composites and polymerization of latex during the matrix hydration process. The optical microscopic images verify the observed macromechanical response.

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