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Pullout behavior of polypropylene fibers from cementitious matrix

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Abstract

A comprehensive experimental investigation was performed to understand the pullout behavior of polypropylene fibers from a cementitious matrix. The effect of embedded length on the pullout characteristics, the development of the interfacial bond with age of curing of matrix and the effect of exposure to degrading environments, like seawater and salt water, on the interfacial bond between the fibers and cementitious matrix were studied. The aim of these experiments was to understand the properties of fiber/matrix interface, which are of primary significance in predicting the overall behavior of fiber-reinforced cement-based composites. Polypropylene fibers have a weak bond with cementitious matrix because of smooth surface of fibers, which does not allow for sufficient friction to develop between the two. In this study a new method to improve the frictional bond by means of mechanical indentations of fibers was also proposed. The bonding performance was characterized by means of pullout tests of the plain and modified fibers from a cementitious matrix. An optimum level of fiber modification for maximization of bond efficiency was determined experimentally.

Keywords: Cement paste; Fiber reinforcement; Polymers; Pullout strength; Bond strength

1. Introduction

Fibers are increasingly being used for the reinforcement of cementitious matrix to enhance the toughness and energy absorption capacity and to reduce the cracking sensitivity of the matrix. Cement-based composites exhibit the general characteristics of brittle matrix composites; that is, the failure of the matrix precedes the fiber failure, thus allowing the fibers to bridge the propagating crack. The toughening effect is the result of several types of fiber/matrix interactions, which leads to energy absorption in the fiber-bridging zone of a fiber-reinforced concrete (FRC). These processes include fiber bridging, fiber debonding, fiber pullout (sliding) and fiber rupture as a crack propagates across a fiber through the matrix [1], as shown in Fig. 1. Although the amount of energy absorption associated with each mechanism for individual fiber may not be significant, a large number of fibers bridging over an extended length can contribute an enormous toughening effect to the composite. Fiber bridging results in crack closure and a reduction in stress intensity factor at the crack tip. Fiber debonding and pullout (sliding) at the interface have a significant influence on total energy absorption during crack propagation. Thus, the fiber/matrix bond strongly affects the ability of fibers to stabilize crack propagation in the matrix. Many researchers have investigated and modeled the effect of the interfacial bond on composite properties such as crack resistance [2,3] and durability [4]. Many researchers have conducted fiber pullout tests using different techniques to characterize the fiber/matrix interfacial bond properties in fiber-reinforced cementitious composites. In this study, the interfacial bond properties between polypropylene fibers and cementitious matrices were studied using single fiber pullout tests. The results obtained from this study are important for better understanding of the role of polypropylene fibers in improving the properties of brittle cement-based composites.

The second part of this study focuses on a new method of improving the fiber/matrix interfacial bond. While polymer fibers have certain advantages over other fiber types, they also have their limitations. One of these limitations is the poor adhesion and wettability to a cementitious matrix as a result of their chemical inertness

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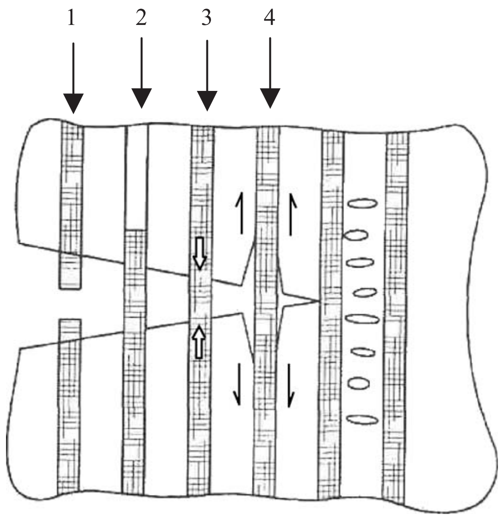

1. Fiber Failure
2. Fiber Pullout
3. Fiber Bridging
4. Fiber/Matrix Debonding

Fig. 1. Energy absorption mechanisms in FRC.

and low surface energy [5], resulting in a weak bond with the cement matrix. Consequently, it is necessary to develop special techniques to enhance the interfacial bond of polymer fibers to utilize the maximum strength of the fiber and to improve the composite properties. The need for enhancing interface properties is especially important for higher modulus, higher strength polymeric fibers that are increasingly being introduced at attractive costs. A variety of interface strengthening mechanisms have been proposed and utilized by various researchers. Some of these make use of macroscopic processes such as fiber deformation, others utilize microscopic changes such as fiber surface and/or transition zone modifications. The interface densification technique utilizes the addition of fine silica fume powder to cement matrix [6]. This technique provides significant bond strength enhancement but is limited to metal and carbon fibers only. For low-surface-energy polymer fibers, fiber deformation and fiber surface modification have been shown to be more effective in improving the interface bond strength [7]. Most fiber deformation processes result in an increase in surface area of contact with the cement matrix per unit fiber length. These processes include fibrillation, crimping and twisting of fibers (shown in Fig. 2(a)–(c)). Another fiber-deformation process, which results in an increase in mechanical anchorage of fibers in cementitious matrix, is the addition of buttons at the ends of the fibers [8], as shown in Fig. 2(d). Finally, surface modification of fibers by means of plasma treatment [9] is also used to improve interfacial bond characteristics in polymeric fibers/cementitious systems. In the presence of a gas plasma, hydrogen atoms are removed from the polymer backbone and replaced by polar groups. The presence of polar functional chemical groups on the fiber surface enhances reactivity and thus improves the adhesion between fiber and cement. A review of the interface strengthening mechanisms in FRC is provided in Ref. [10]. In this study, a new fiber surface modification technique has been proposed and shown to be effective in

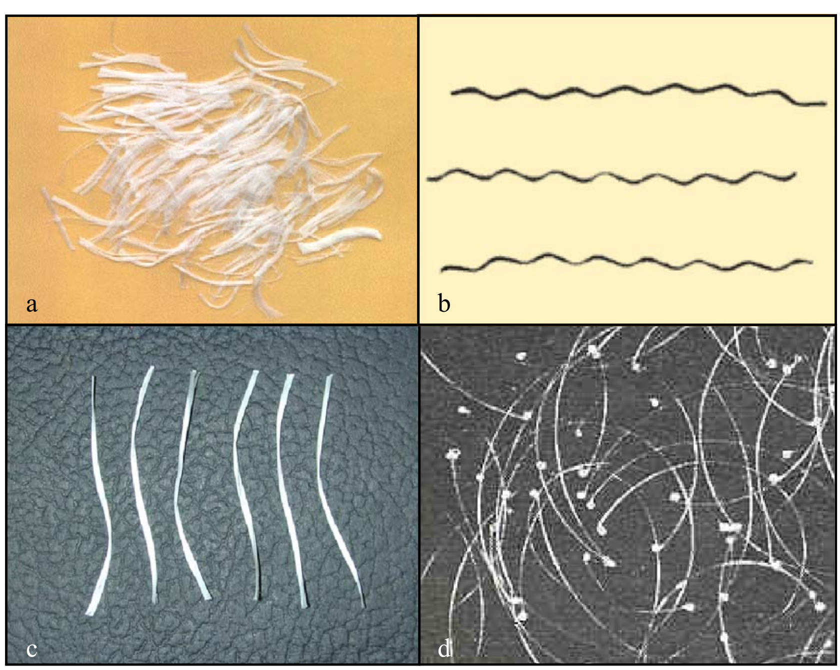

Fig. 2. Fiber deformation processes for bond improvement.

improving the interfacial bond strength between polypropylene fibers and cement matrix.

2. Experimental investigation and results

2.1. Pullout samples and experimental procedure

Pullout of a fiber from a cement-based matrix was used to characterize the interfacial bond between the matrix and the fiber. A schematic of the pullout sample used in this study is shown in Fig. 3. These samples were cast in 2-mm diameter, 50 mm long plastic cylindrical molds. Wet cement mortar was poured in the mold, and the fiber was introduced from the top and held there by a slot in the lid of the mold. A bolt was cast in the samples on the side opposite to the fiber to hold the sample on an Instron testing machine through a threaded steel block. The samples were allowed to harden in air for 24 h and then placed in a wet bath for a period of 7 days, after which, the pullout tests were carried out. The sample was held on the Instron testing machine, and the fiber was loaded in tension until the fiber debonded and was withdrawn. The rate of pullout used in this study was 0.02 mm/s. The pullout load and the end displacement of the fiber were continuously recorded and were used to develop pullout load versus end displacement curves. These curves were used to obtain the peak pullout loads and pullout energies (toughness) by calculating the area under the curves. The following materials were used in this experimental program: matrix—mortar (cement/sand = 0.5, water/cement = 0.35); fibers—Strux 85/80, provided by Grace Construction Products, MA. These are thin strips of polypropylene, 50 mm long and have a rectangular cross-section of 1.25 × 0.2 mm. A picture of these fibers is shown in Fig. 4.

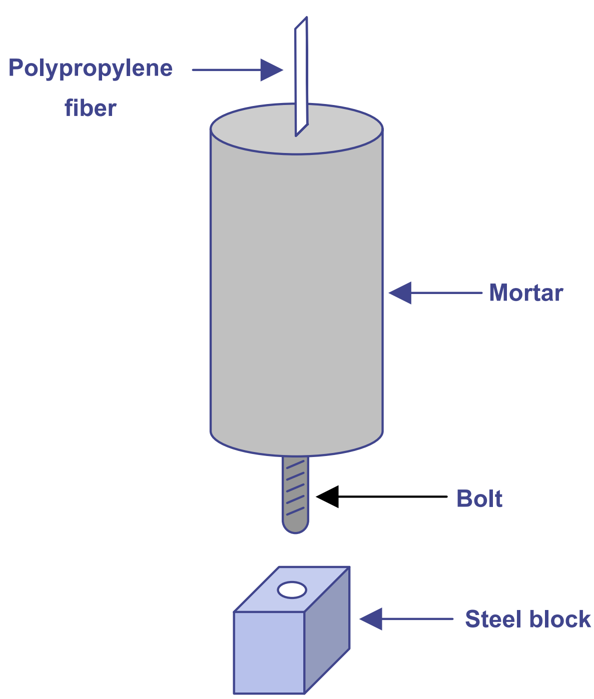

Fig. 3. Schematic of the pullout test sample.

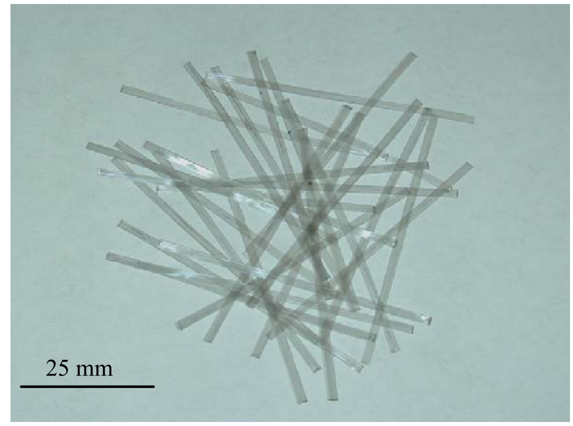

Fig. 4. A picture of the fibers used in this study.

2.2. Pullout behavior of Strux fibers

The pullout tests of Strux polypropylene fibers from cement matrix were carried out to investigate the effect of embedded length on the pullout characteristics, the development of the interfacial bond with the age of curing of matrix and the effect of exposure to degrading environments, like seawater and salt water, on the interfacial bond. The bond strength was calculated from the peak load and the embedded area of the fiber. The area under the pullout curve up to 5 mm pullout displacement was calculated to obtain the interfacial toughness. This corresponds to the energy absorbed in the pullout process up to a pullout displacement of 5 mm. The energy absorbed was calculated up to 5 mm pullout displacement because a 5- to 10-mm crack opening is far beyond the acceptable limit for most practical structures. A typical pullout curve of the fibers used in this study is shown in Fig. 5. It can be seen from this plot that the pullout load initially increases almost linearly with the slip. The nonlinear region indicates the start of debonding of the fiber from the matrix. The interfacial debonding can be considered as a Mode II fracture. This interfacial crack stably propagates up to peak load; that is, the crack propagates only when the pullout load increases. After the peak load, unstable crack growth occurs, which means that the crack grows even though the pullout load decreases. Finally, the fiber starts slipping out of the matrix.

The average pullout strength of these fibers, for an embedded length of 25 mm, based on 17 samples, was 24.5 ± 2.1 N. The average interfacial toughness for the 17 samples tested was found to be 0.122 ± 0.010 Nm.

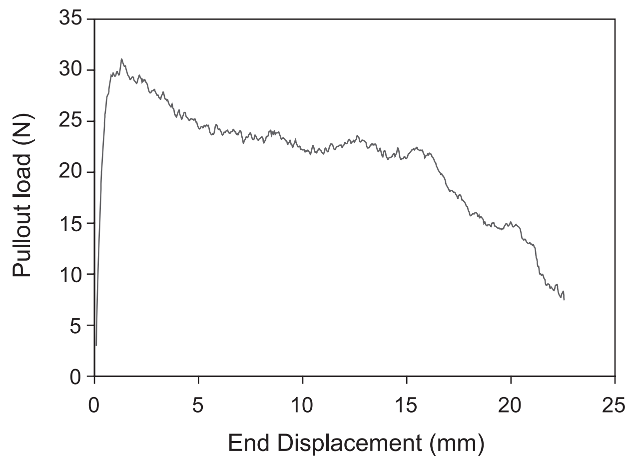

Fig. 5. A typical pullout of curve of Strux 85/80 fiber.

2.3. *Effect of embedded length on the pullout characteristics*

Pullout tests were carried out for three different embedded lengths (19, 25 and 38 mm) of Strux fibers in cement mortar. It was found that the peak pullout load increases with the increase in embedded length. With an increase in the embedded length, the pullout characteristics of the fibers also change. The pullout curves for the three embedded lengths are shown in Fig. 6, where A, B and C correspond to the three embedded lengths of 19, 25 and 38 mm, respectively. With an increase in embedded length, the part of the curve corresponding to frictional sliding shows an increase in the pullout load. This increase can be attributed to the increase in friction between the fiber and matrix due to the abrasion of the fiber as it slides out of the matrix. The abrasion effect tends to increase with the increase in embedded fiber length. The plot of the peak pullout loads versus embedded length is shown in Fig. 7. The error bars shown on the graph are of 95% confidence intervals, calculated using Student's *t* distribution. The shear strength of the bond based on the peak loads was calculated for the three embedded lengths, and it was found that it is almost constant, with a value of around 0.5 MPa, as shown in Fig. 8.

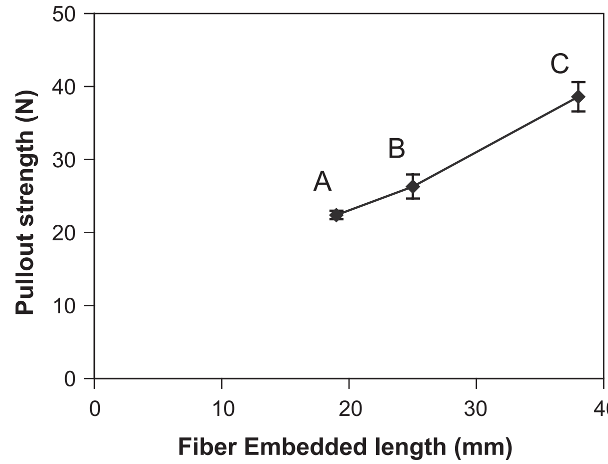

Fig. 7. Peak pullout loads for three different embedded lengths. (A) 19 mm (B) 25 mm (C) 38 mm.

2.4. *Effect of curing age of matrix on the pullout characteristics*

The mechanical properties of cement-based materials are time dependent due to prolonged cement hydration process. In FRC, mechanical behavior may also be time dependent due to the aging effect, not only on the matrix properties but also on the fiber/matrix bond properties. The contrast in the rate of development between interfacial bond and various other properties of the matrix could result in a complicated composite age-dependent behavior compared with ordinary cement materials, especially at the early age. Thus, it is important to understand the development of interfacial bond with the curing age of matrix.

A batch of pullout samples was prepared, and tests were carried out after the first 8 and 24 h and each subsequent day

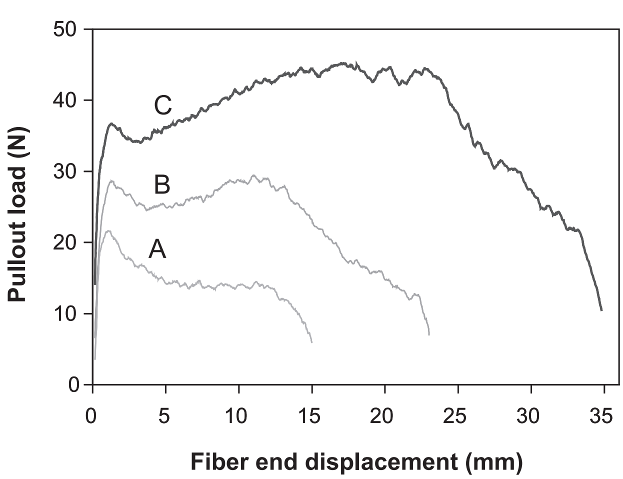

Fig. 6. Pullout plots for three different embedded lengths. (A) 19 mm (B) 25 mm (C) 38 mm.

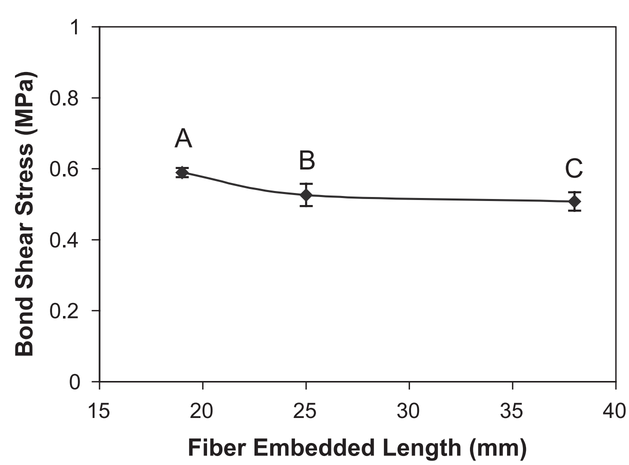

Fig. 8. Bond shear stress for three different embedded lengths. (A) 19 mm (B) 25 mm (C) 38 mm.

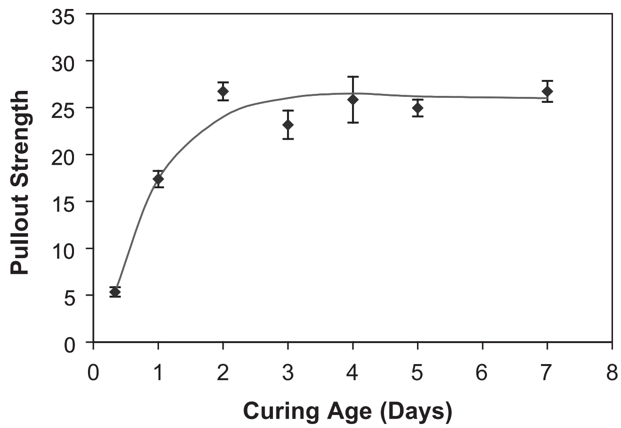

Fig. 9. Development of bond strength with curing age of matrix.

after that for a period of 7 days. The peak pullout loads from this test scheme are plotted in Fig. 9. It was found from these tests that the interfacial bond achieves its maximum strength within the first 2 days of curing, and the further curing of matrix has no effect on the interfacial bond. This is in contrast to the development of the properties of matrix, which is a prolonged process.

2.5. Effect of degrading environments on pullout characteristics

Although polypropylene is fairly resistant to chemical agents such as acids, alkalis and salts [11], concrete is known to degrade under the attack of seawater [12]. The diffusion of aggressive ions present in seawater results in a series of chemical reactions, leading to the degradation of concrete and also to the alteration of its microstructure. Changes in the microstructure at the interfacial zone may also affect the fiber/matrix interfacial bond, which is mainly mechanical in nature. To study the effect of seawater and salt water on the interfacial bond properties, a batch of 24 pullout samples was prepared. After curing

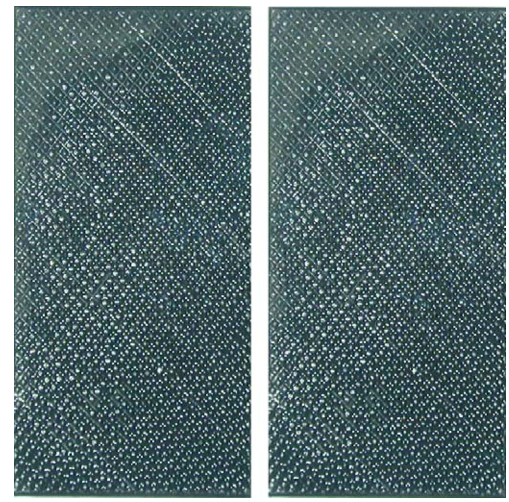

Fig. 11. Picture of indenting surfaces.

for a period of 28 days, six samples were tested to obtain baseline data and six samples each were placed in plain water (control), salt water (5% weight fraction) and seawater. These samples were tested after a period of 6 months. The 28-day average pullout strength was 24.0 ± 1.0 N, and the average pullout strength of the samples exposed to plain water, salt water and seawater for 6 months was, respectively, 24.5 ± 1.6, 27 ± 1.0 and 30.3 ± 1.3 N. A comparison of the pullout curves for the samples exposed to plain water, salt water and seawater is shown in Fig. 10. The pullout curves shown are average of six samples for each of the environments. It can be observed from these results that the pullout strength of samples exposed to salt water and seawater is more than those kept in plain water, with the pullout strength of samples exposed to seawater being maximum. The change in the microstructure of concrete at the interfacial region with exposure to seawater, resulting in

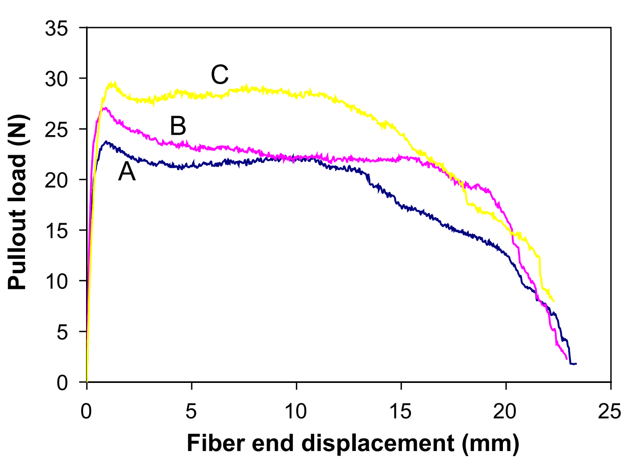

Fig. 10. Average pullout curves for samples exposed to (A) plain water, (B) salt water and (C) seawater.

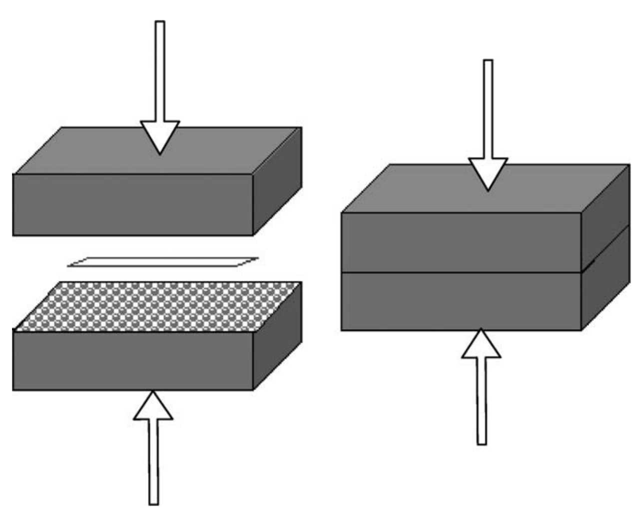

Fig. 12. Schematic of the indenting procedure.

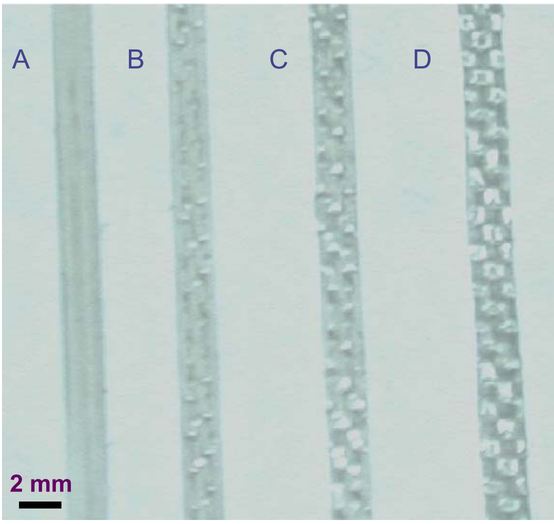

Fig. 13. A picture of plain and indented fibers.

an increase in interfacial friction, could be the reason behind this phenomenon.

3. A method for improvement of interfacial bond

A new method for improving the interfacial bond between polypropylene fibers and cement mortar matrix is proposed. In this method, mechanical indentations were created on the fiber surface by pressing the fibers between two hardened steel surfaces having projections. A picture of the indenting surfaces is shown in Fig. 11. The fibers were placed, one at a time, between the two surfaces, and the surfaces were pressed together on an Instron testing machine at known loads. Three different levels (pressures) of indentation were used, and pullout tests were carried out with the fibers thus modified. A schematic of the indenting procedure is shown in Fig. 12.

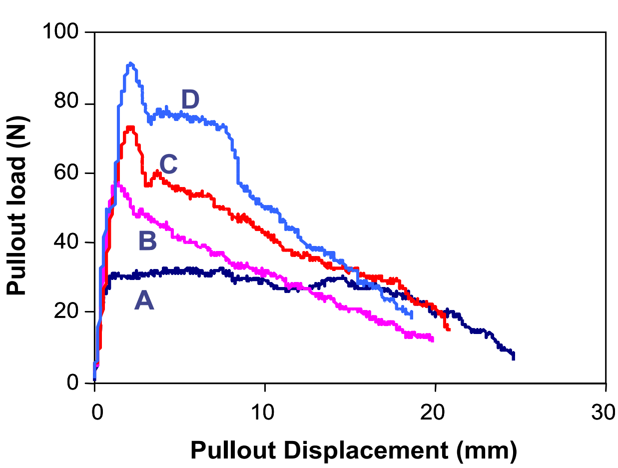

Fig. 14. Pullout curves of plain and indented fibers.

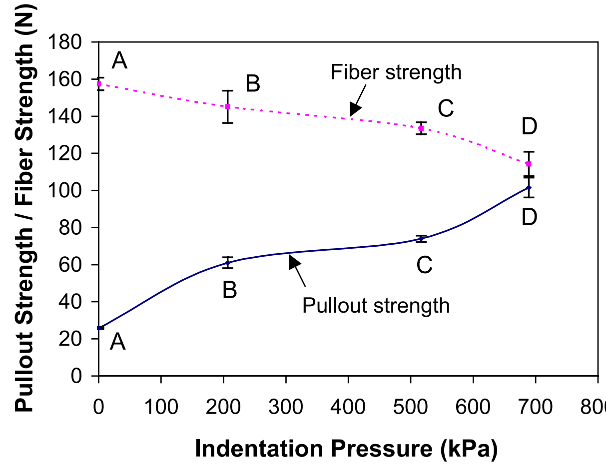

Fig. 15. Peak pullout loads and strengths of fibers with different levels of indentation. (A) Plain fiber, (B) indentation pressure = 200 kPa, (C) indentation pressure = 500 kPa and (D) indentation pressure = 200 kPa.

3.1. Pullout of indented fibers

A picture of a plain fiber (A), along with fibers having three different levels of indentations, is shown in Fig. 13. Three levels of indentation were obtained by pressing the fiber between the two surfaces at three different pressures of 200, 500 and 700 kPa (B, C and D, respectively). Fig. 14 shows the comparison of the pullout curves of these four fibers. The average pullout strengths of the Fibers A, B, C and D are 25.8 ± 0.5, 61.0 ± 2.9, 73.9 ± 1.4 and 101.6 ± 5.3 N, respectively. The pullout strength of fibers with the indentation level of 700 kPa is three times the pullout strength of plain fibers. The peak pullout loads of these fibers are plotted in Fig. 15. The figure also shows the decrease in the fiber strength with increasing indentation. This plot shows that using this indentation procedure, an indentation level of 700 kPa would be the most optimum for the maximum utilization of the fiber strength. At this indentation level, the fiber would just pull out of the matrix, without breaking, and thus provide maximum crack closing force and maximum energy absorption. These deformations can be easily created on the fibers on a large scale in the following way. Extruded sheets of polypropylene can be passed through rollers having projections, pressed together at the required load, using a mechanism capable of adjusting

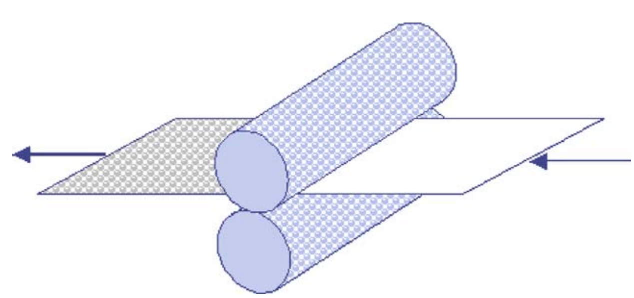

Fig. 16. Schematic of the suggested indenting procedure on a large scale.

the pressure between the two rolls. A schematic of this process is shown in Fig. 16. The sheets thus produced with indentations can be slit longitudinally into tapes, which can be cut to the required length to obtain the fibers.

4. Conclusions

A comprehensive experimental investigation was carried out to evaluate the pullout behavior of polypropylene fibers from cementitious matrix. These data would be helpful in better understanding the behavior of the fibers in the cementitious matrix and, also, the overall behavior of the composite. Based on these experiments, the following conclusions can be drawn.

- With the increase in embedded length, fiber abrasion effect becomes prominent and results in an increase in pullout load in the frictional sliding zone of the pullout.
- The fiber/matrix interfacial bond attains its maximum strength within the first 2 days of curing of the matrix, unlike the strength development of the matrix, which is a long process.
- The effect of degrading environments, like salt water and seawater, on the interfacial bond strength was also evaluated. Based on the pullout tests, the fiber/matrix bond strength was found to increase with exposure to salt water and more so with exposure to seawater. The reason behind this observation could be a change in the microstructure of concrete with exposure to such environments, leading to an increase in friction between the fibers and matrix.
- Finally, a fiber surface modification methodology for improving the interfacial bond properties between fiber/cement using mechanical indentations of fibers was proposed. The maximization of bond strength and interface toughness can be achieved with optimum level of indentations, as illustrated for polypropylene fibers. The bond strength between polypropylene fibers and cement matrix was shown to increase by a factor of three with optimum level of modification. This result may have important implications in optimal design of FRC. This method can be used for other high-strength, high-modulus polymer fibers. By improving the fiber matrix bond, it is possible to use lower fiber aspect ratio or volume fraction in FRC while retaining essentially the same crack resistance.

Acknowledgements

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