Performance of Fibers Embedded in a Cementitious Matrix

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Received 17 May 2009; accepted 11 September 2009
DOI 10.1002/app.31524
Published online 23 December 2009 in Wiley InterScience (www.interscience.wiley.com).

ABSTRACT: Reinforcement of cementitious materials with short fibers has been proved to be an economical and effective way to convert these brittle materials to ductile products. Many fibers with different geometries have been used as reinforcement materials. Fibers bonding to cementitious materials play an important role in mechanical performance of these composites. This article describes the performance of (homemade) fibers as reinforcement in cement-based materials by investigation on bonding characteristic of fiber to cement matrix. To this end, the fibers (glass, polypropylene, polyacrylonitrile (PAN), and high strength nylon 66 (N66)) are characterized using microscopy analysis, tensile strength, and alkali attack tests. The fibers embedded in the cement matrix, then, pulled-out to evaluate their bonding to cementitious materials. SEM analysis is used to study fiber/cement interfacial transition zone. The results show that PAN fibers have the advantages of preparing for cementitious reinforcement. It was found that the reinforcing efficiency of fibers-reinforced cementitious composites was strongly depending on interfacial contact area in fiber/matrix interface and chemical/physical properties of fibers. © 2009 Wiley Periodicals, Inc. J Appl Polym Sci 116: 1247–1253, 2010

Key words: fibers; bonding; pull-out; cementitious composites

INTRODUCTION

Cementitious materials are inherently brittle. To do away with this problem, the application of discrete short fibers has been proposed.[1] Today, reinforcement with fibers has been proved an effective and economical way to convert cementitious material into a tough and ductile product.[2] Fiber-reinforced cement-based composites have been used in structures subjected to seismic loads, bending and/or shear loads, such as, precast elements, roofing, offshore constructions, large bridge slabs, footings, tunnel linings, structures with higher load-carrying capacity, and other various structures.[1]

Since the beginning of the 20th century, asbestos fibers were extensively used as reinforcement to produce cement sheets.[3] Asbestos fiber has an excellent bonding to cement matrix and, consequently, causes better performance of cement composites. Because of its desire properties, during the last century asbestos was used for various building materials. Despite of outstanding properties, the usage of asbestos fibers has been restricted in cementitious composites since 1980 in many countries because of its dangerous to health human at all stages of asbestos fiber extraction and handling.[4] In last decades, many efforts have been made to replace these fibers by many types of fibers. Thereafter, different fibers have been produced and used for reinforcing cement-based materials, then stimulated extensive research directed at other kinds of substitute fibers.[5]

The most frequently used reinforcing fibers are organic fibers (such as acrylic, polyvinyl alcohol, polyethylene, polypropylene (PP), and nylon), natural cellulose (such as hardwood and softwood pulps), and inorganic fibers (glass and carbon).[6] Because of many advantages of polymeric fibers as reinforcement, such as, good availability, suitable properties (especially, chemical resistance), formability, and different geometries, they were considered by construction applications.

Fibers usually do not enhance the strength of cementitious composites but improve their crack opening and propagation and develop energy absorption and ductility in cement-based materials.[7] Fibers can act in two ways in cement-based composites: (1) The improvement of the flexural/tension properties of the composites, (2) preventing crack creation and propagation in the cement matrix by bridging on micro-cracks.

The performance of cementitious composites under mechanical loads depends on many factors, including fiber material properties (fiber type, strength, stiffness, and Poisson's ratio), fiber geometry (fiber surface and cross-sectional), fiber volume content, their dispersion and matrix properties (matrix strength, stiffness, Poisson's ratio), and interface

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Journal of Applied Polymer Science, Vol. 116, 1247–1253 (2010)

TABLE I
Properties of Fibers

Fiber type	Tensile strength (cN/dtex)	Elongation at break (%)	Linear density (dtex)	Elastic modulus (cN/dtex)
PP	2.82	174.49	5.79	11.42
N66	8.89	27.34	6.70	41.65
PAN	2.88	45.56	14.40	50.45
E-glass	6.49	1.98	9.14	288.45

properties (adhesion, frictional and mechanical bond).[8] Therefore, many studies have been carried out on the effect of fiber properties on mechanical characteristics of resultant cement-based composites and found their importance.[9–13] Jamshidi and Karimi investigated application of polymer fibers as reinforcement in cementitious matrix. They used flexural strength test to evaluate performance of different fibers in composite. They found that composite depends on fiber's type (chemical composition), content, shape of fiber, etc. They also investigated interfacial transition zone (ITZ) between used fibers and cement matrix by microstructural study and found that affinity (bonding) of fibers to cement matrix play an important role in the composite performance.[14]

It is mentioned by other researchers that fiber bonding to cement matrix is crucial parameter in crack opening control and increases the energy demand for the crack propagation.[15–17] Thus, the mechanical performance of fiber reinforced composites, such as, strain capacity or ductility and tensile strength, strongly depends on the debonding/pull-out behavior of fibers from cement matrix.[18–20]

Hence, an important research topic is the need to know pull-out behavior of fibers. Conventional method for investigation on interface properties of fiber/cement matrix is pull-out tests, which were conducted by pulling individual fibers out of cement matrix.[21,22]

In this study, four homemade fibers including polyacrylonitrile (PAN), PP, nylon 6,6 (N6,6), and E-glass fibers were used to reinforce cementitious paste. The fibers were characterized for physical/mechanical properties and alkali resistance. To study performance of fibers in cement matrix, single fiber pull-out test were used and bonding strength were measured.

MATERIALS

The Portland cement Type II of Tehran cement Co. was used for the experimental work. The fibers used in this study were PP, N66, PAN, and E-glass monofilaments, which were manufactured by Iran Polyacryl Co., Zanjan's Tire Cord Co., Polypropylene Manufacturing Co., and Iran Glass-Wool Company, respectively.

EXPERIMENTAL

Physical/mechanical properties of fibers

The single fiber tensile test is performed to determine the tensile strength and the properties of the used fibers. The test is performed using the Fafogarph machine. The curves of stress versus displacement are prepared for each specimen and the tensile property is calculated. Information of fibers properties summarized in Table I. Fibers cross-section is also studied by optical microscope (OM).

Pull-out test setup

Pull-out specimens are prepared by embedding 10 mm length of single (filaments) fibers in the cement matrix. The schematic of the apparatus for preparation of pull-out samples is shown in Figure 1. At first, the lower parts were fixed carefully to the base plate. Then, filament fibers were aligned and fixed on the double side adhesive tapes that were justified on the fixer frame. When fibers were adjusted, the outer parts to perform specimen preparation mold. This operation should be done in absence of any stretch in fibers. The all-parts surface in contact with fibers were covered by thin layer of a silky material to tight the fibers. After assembling of all parts, cement matrix was filled in mold.

Sample was demolded 24 h after casting and it was cut into the pull-out test specimens as shown schematically in Figure 2, then, they were cured in a humidity chamber room for 28 days.

The pull-out test setup is illustrated in Figure 3. The pull-out test was conducted using a tensile

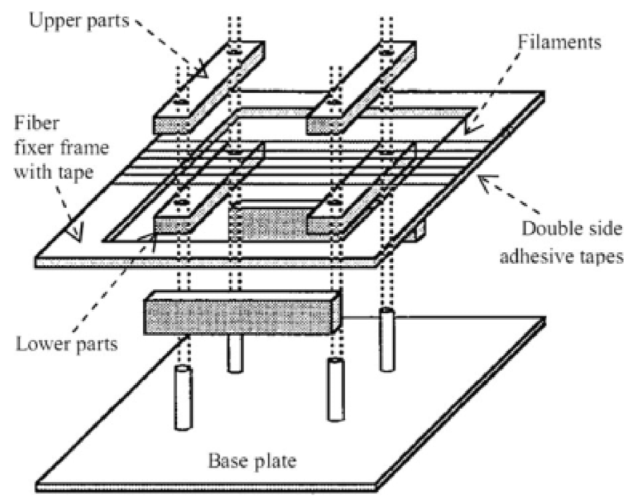

Figure 1 Schematic of mold assembly for pull-out specimen preparation.[20]

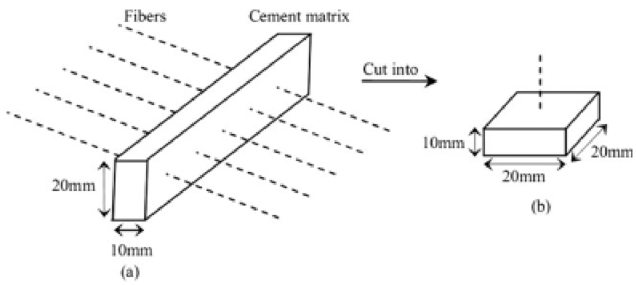

Figure 2 Schematic of: (a) demolded pull-out sample, (b) single fiber pull-out test specimen.

testing machine with constant rate of displacement. The cement specimens were held by a fixture (specimen holder). The upper end of specimen holder was held by upper fixture of tensile testing machine. The protruded fiber end attached to a small Plexiglas cube by super glue. This cube fixed by lower fixture of tensile testing machine. When tensile machine beginning to apply load, fiber draw out of matrix. In general, pull-out strength properties were interpreted based on load-displacement curves from the pull-out test. For each fiber, five specimens were tested and mean value was reported.

Alkali resistance

Because of its hydration process and the generation of $Ca(OH)_2$, Portland cement is a strong alkali environment, which can cause the degradation of some fibers. The degradation of fibers decreases their tensile strength and, consequently, the mechanical performance of cementitious composites. Therefore, it is important to investigate the alkali resistance of used fibers in cementitious composites. To evaluate the resistance, fibers are soaked in NaOH with pH = 12. The tensile strength of fibers is tested after 28 and 56 days.

RESULTS

Alkali resistance of fibers

Figure 4 presents the load-extension curves of PAN fibers at different periods of alkali treatment. Test

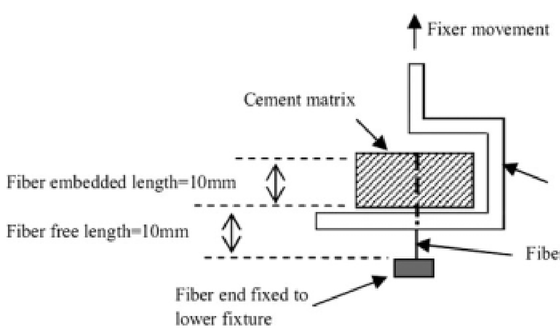

Figure 3 Schematic of pull-out test setup.

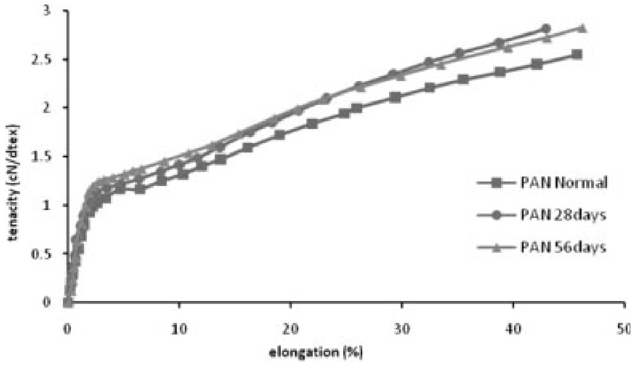

Figure 4 Tensile behavior of PAN fibers at different periods of alkali treatment.

results revealed that these fibers have excellent chemical stability in alkali environments. Thus, it can be concluded that PAN fibers are appropriate for being applied in cementitious composites.

Alkali resistance test results for N66 fiber show that fiber's tensile strength is not changed during exposure to alkali environments (Fig. 5). It is evident that the fiber elongation after alkali treatment is slightly increased. Increase in the fiber elongation after exposure to alkali environment after 28 and 56 days were 12.04% and 16.78%, respectively.

Figure 6 shows the test results of PP fibers. No changes in the fiber strength after soaking in alkali for periods of 28 and 56 days were observed (Fig. 6). The PP fibers have excellent resistances against alkalis.

Figure 7 shows the tensile behavior of E-glass fiber after soaking in alkaline solution. It is evident that the fiber strength considerably decreases. The strength of E-glass fiber is rapidly decreased in the alkali environment, notably at 56 days exposed specimens. Therefore, it is concluded that glass fibers (E-class) are not appropriate for cementitious materials reinforcement. According to weak performance of E-glass fibers in alkali condition, especially in long-term exposures, they are not advised

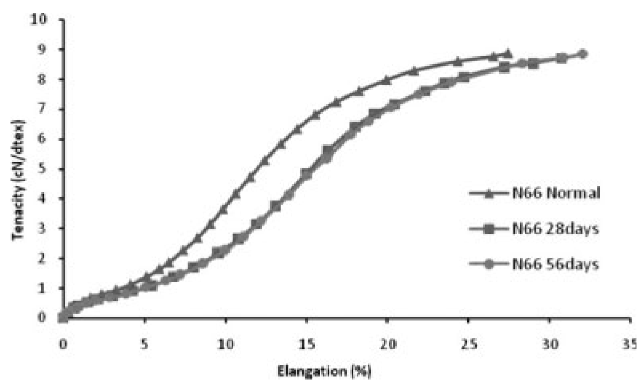

Figure 5 Tensile behavior of N66 fibers at different periods of alkali treatment.

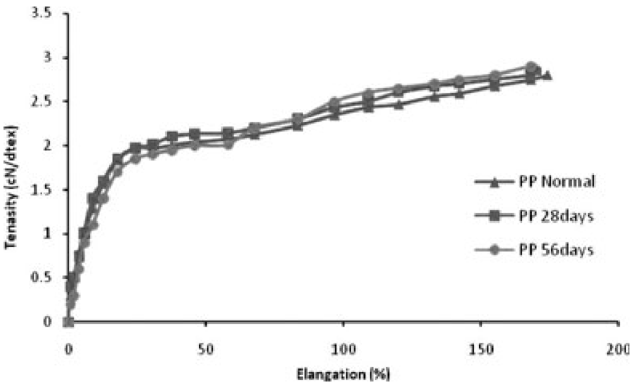

Figure 6 Tensile behavior of PP fibers at different periods of alkali treatment.

to be used in reinforcement of cementitious composites due to decreasing the composite strength.

Optical microscopy analysis

The cross-section of PAN, PP, and N66 fibers are observed by OM, Figures 8–10. N66 and PP fibers have round-shaped cross-sections. Figure 10 presents the PAN fibers cross-section. It is obvious that PAN fibers have bean-shaped cross-sections, which is formed due to wet spinning processing of PAN fibers.

Pull-out test

Figure 11 shows the result of different fibers pull-out from 28 days cured cement matrix. Initial stage in all pull-out curves is contributed to the debonding process at the very beginning stage and concave-downward shape of nonlinear segment indicates a slip-hardening behavior of fiber pull-out.[23] It is evident that PAN fibers have higher pull-out strength in comparison with other fibers. The sudden decrease in pull-out strength of PP and PAN fibers shall be related to fracture failure of these fibers. For N66 fibers, debonding (slippage) behavior of fiber from cement matrix was observed. The bond strength of PAN fibers to cement matrix, as shown in Figure 14, is in the vicinity of fibers' tensile strength. Fiber/matrix bond is estimated equal approximately to 2.36 cN/dtex, which is close to its fiber tensile strength, 2.88 cN/dtex.

The higher bonding of PAN fibers to cementitious matrix can be attributed to two parameters of: (a) chemical affinity of acrylic polymers to hydration cement products,[12] (b) noncircular cross-section of this fiber which cause higher specific surface area and more surface to interlock with cementitious matrix.

It is well-known that PP fibers have hydrophobic nature and cannot be wet by cement paste. Adversely, N66 fibers have hydrophilic nature and it is expected to result in better bonding strength than

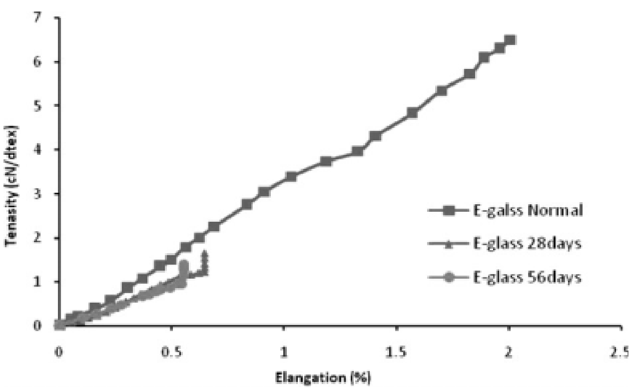

Figure 7 Tensile behavior of E-glass fiber at different periods of alkali treatment.

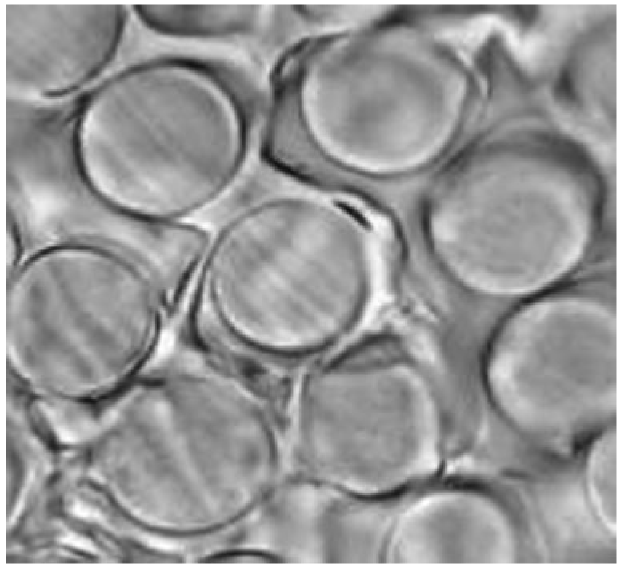

Figure 8 Cross-section of N66 fibers.

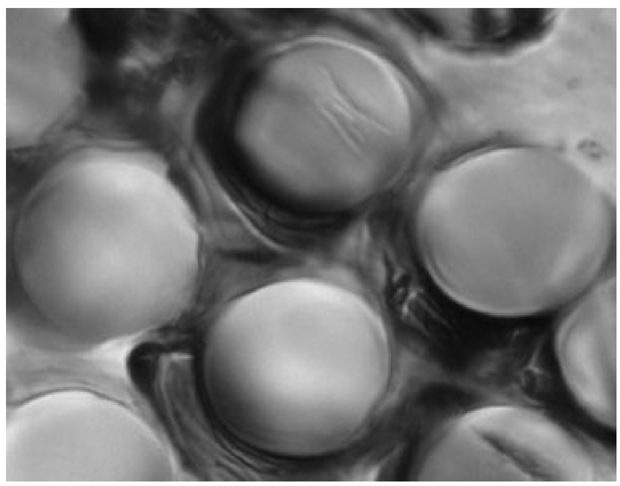

Figure 9 Cross-section of PP fibers.

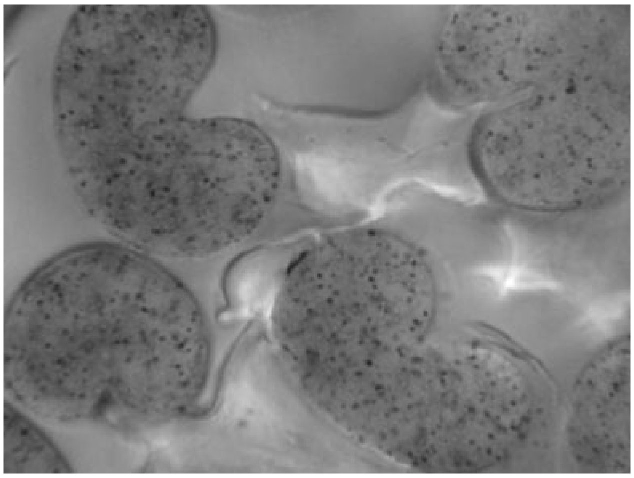

Figure 10 Cross-section of PAN fibers.

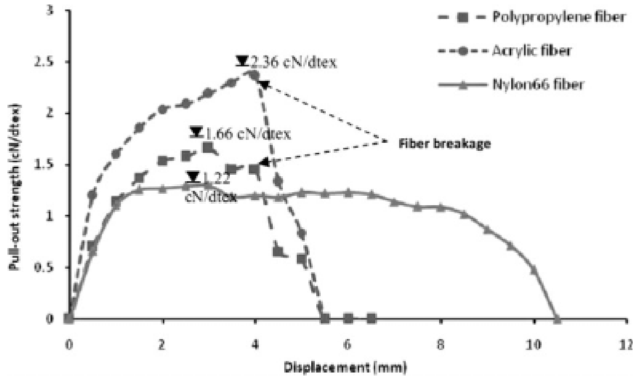

Figure 11 Pull-out behavior of different fibers from cement matrix.

PP fibers to cement paste but a challenging result was obtained in this investigation. The better bonding result of PP fibers shall be attributed to energy dissipation and stress damping capabilities, which are important factors in fracture mechanism for increasing bonding energy at interface of adherent materials. The energy dissipation and damping of PP fibers are related to physical properties of fiber (higher modulus of elasticity and more elongation comparing with other fibers).

In the case of PP fibers, the bonding strength (1.66 cN/dtex) is slightly far from their tensile strength (2.82 cN/dtex), but fibers failed gradually during pull-out test. This may be due to mechanical degradation (i.e., decrease in diameter and deep scratches on fibers).

The N66 fibers show good pull-out behavior from the cement matrix and the pull-out strength (1.22 cN/dtex) is much lower than the fiber tensile strength (8.89 cN/dtex).

SEM analysis

The longitudinal surfaces of fibers before using for pull-out test and after drawn from cement matrix were analyzed using scanning electron microscopy (SEM).

Figure 12 presents the SEM micrograph of a PAN fiber and a PAN fiber after drawn from cement matrix. A layer of hydrated cement products is deposited on the surface of the pulled-out fiber. The crystalline particles can be clearly seen on the fiber fossa.

PAN fiber exhibited the highest values in bonding strength than other fibers. This was early due to the wider interfacial contact area between reinforcement and cement matrix that could effectively transfer the applied load. Also, SEM micrographs revealed good adhesion of PAN fibers to cement hydrated product. So, bonding performance of PAN fibers was attributed to both the hydrophilic nature of PAN and the shape effect of fibers.

Observation of PP fibers after drawn from matrix indicated its severe friction to cement matrix during

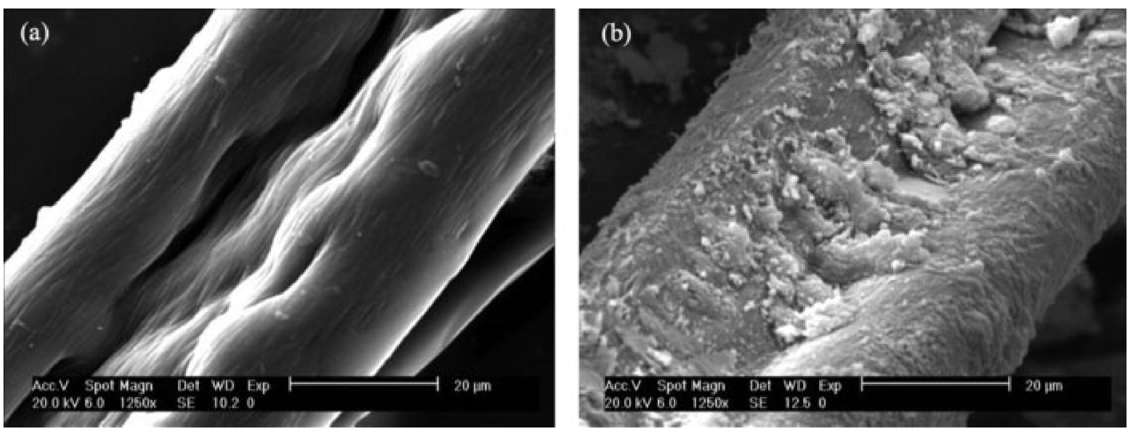

Figure 12 SEM micrograph of a PAN fiber: (a) Before using in cement matrix, (b) after pulled-out from cement matrix.

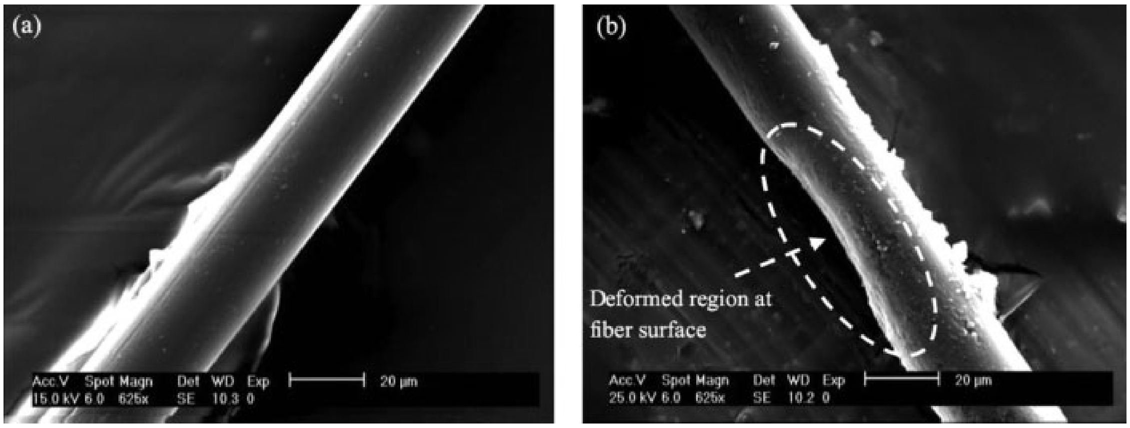

Figure 13 SEM micrograph of a PP fiber: (a) Before using in cement matrix, (b) deformed PP fiber after pulled-out from cement matrix.

pull-out test as shown in Figure 13. The scratched and deformed area of a PP fiber during pulling-out due to the interior stress at lateral surface of fiber can be seen in Figure 13 (a). The lack of cement hydration products on PP fibers after pull-out reveals authors suggestion about weak chemical bonding and strong mechanical interlocking between PP fiber and cement matrix. It can be concluded from pull-out test results and SEM micrographs that PP fibers use another mechanism; energy dissipation and pull-out stress damping by deformation of fiber instead of chemical bonding.

Figure 14 presents SEM micrographs of N66 fiber before using in cement matrix and after pull-out test. It is evident that there is better affinity between this fiber and the cement paste compared with PP fibers. Hydrated cement particles on the fiber surface indicates the presence of chemical adhesion between the cement paste and the N66 fibers. It can be attributed to hydrophilic property of N66 fibers.

Because of good chemical interactions to cement matrix, better bonding can be prospected for N66 fibers in comparison with PP fibers. Unlike this prediction, N66 fibers showed weaker bonding strength because of their higher modulus of elasticity, which transfer whole pull-out load to fiber/cement interface. This causes in destruction of interfacial interactions and results in slippage of fiber through the cement matrix under pull-out load.

CONCLUSIONS

The following conclusions are based on the results reported in this article:

1. E-glass fibers are degraded in alkali condition; therefore, these are not advised to be used as reinforcement in cement-based materials.
2. N6,6 and PAN fibers showed interfacial chemical interactions with cement paste.

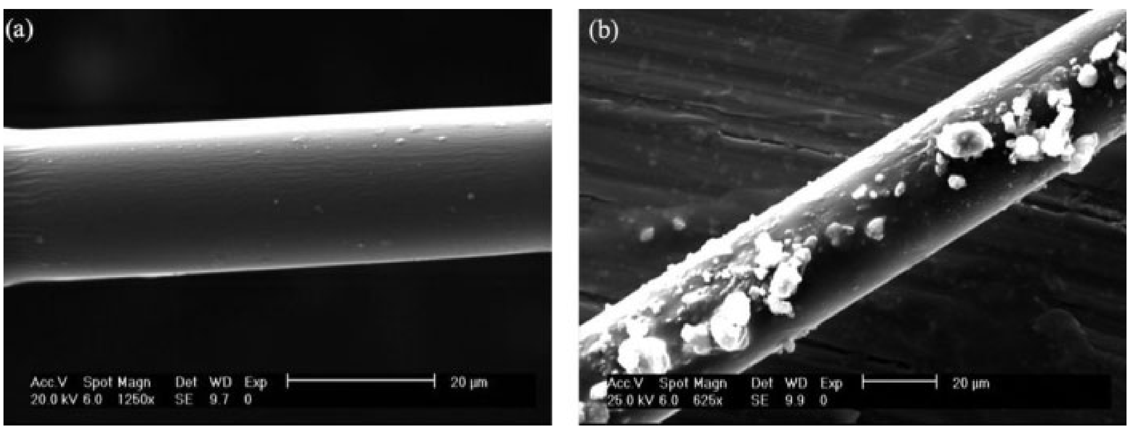

Figure 14 SEM micrograph of a N66 fiber: (a) Before using in cement matrix, (b) N66 fiber after pulled-out from cement matrix.

3. PAN fibers showed the highest bonding strength to cement-based matrix by which this contributed to chemical interactions and mechanical interlocking (due to bean-shape cross-section).
4. PP fibers, in spite of hydrophobic nature and weak wetting by cement paste, showed better bonding than N6,6 fibers. This was attributed to deformation capability of these fibers, which damp pull-out load.
5. The results illustrated role of chemical composition, physical/mechanical properties, and shape factor (contact area between fiber and matrix) of fibers on bonding to cementitious materials.

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