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A STUDY ON BONDING STRENGTH OF POLYMERIC FIBERS TO CEMENTITIOUS MATRIX

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ABSTRACT
Cementitious materials are brittle in nature. Due to this behavior, short, randomly and distributed fibers are mostly being used to reinforce cementitious materials. Added fibers enhance tensile strength and flexural toughness and reduce crack creation and propagation in cement matrix. The major effect of fibers is to act as bridging at crack tips to resist crack propagation. Fiber bonding to cement paste is an important factor that affects performance of the fiber reinforced cementitious composite (FRCC). Bonding energy (adhesion) between these materials is composed of interfacial interactions (chemical bonding) and mechanical interactions (interlocking). The adhesion of fiber to cementitious materials can be evaluated by pull-out test. This test is the newest method and one of the most commonly used practical methods to evaluate performance of fibers in FRCCs.

This article presents the bonding strength results of commercial polymeric fibers to cement matrix. To investigate adhesion of polypropylene (PP), nylon66 (N66) and acrylic (PAN) fibers to cement matrix a single fiber pull-out test setup is designed and fabricated. The specimens were prepared at the water-cement ratio of 0.4 and they were tested at 7, 14 and 28 days of curing. Fiber's surface after pull-out test was also studied by microscopic analysis. Some interesting results were obtained from the pull-out test of different fibers. On the basis of results, it was found that fiber should be selected for FRCC reinforcement due to their mechanical interactions and physical/chemical/mechanical behavior in cement matrix instead of their chemical interactions.

Keywords: adhesion, pull-out test, interfacial interactions, polymeric fibers

1. INTRODUCTION
The application of fibers to reinforce cementitious materials is an ancient subject. At first, asbestos fibers were used in industrial process to produce fiber reinforced cement sheets. Because of their great fiber strength and durability, high physical and chemical resistance, none-combustibility and resistance to weathering attack and cost effectiveness, they were used as building material during the last century with various forms and styles to suit different needs. Despite of these properties,

they can cause a major health hazard to human's safety [1]. Hereafter, various types of synthetic fibers were produced and used as asbestos substitutes.

The performance of FRCC depends on many factors, such as fiber material properties (fiber strength, stiffness, and Poisson’s ratio), fiber geometry (fiber surface and cross section), fiber volume content, matrix properties (matrix strength, stiffness, Poisson’s ratio), and interface properties (adhesion, frictional and mechanical bond) [2].

Bonding depends on the structure of the fiber-matrix interface. Fiber bonding to the cementitious matrix is an important and effective parameter on fiber reinforced cement composites. Also, the performance of fiber reinforced composites is strongly related to the debonding/pull-out behavior of the fibers. For this purpose, the relationship between the pull-out load and the displacement of a fiber, when it is pulled out from the cement matrix, serves as an important parameter in the design of cement composite materials.

Many researchers have been done on the evaluation of bonding between fibers and cement matrix [3-5, and 6]. Some methods and equipments were adapted for pull-out test to evaluate fiber/cement bond strength in the present work.

Fiber pull-out behavior contributes to the energy absorption ability of fibers in FRCCs. Fiber to cement bonding allows stress transfer between them. Regarding to the importance of this behavior in composite materials, fiber/cement interface has been studied in this research.

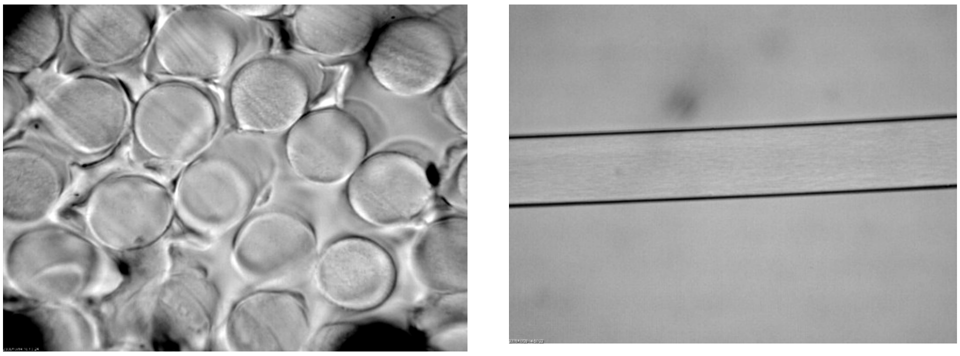
The aim of the present work is to characterize the bonding mechanisms of polymeric fibers to cement matrices. To determine the bond strengths of polymeric fibers to cement matrix, pull-out test was employed. The test setup was basically similar to the numerous techniques that have been developed by previous researchers. Besides the testing setup, it is also important to understand the way that pull-out specimens are prepared. A new technique for preparing specimens for pull-out test was suggested in this work. Fiber pull-out specimens were prepared with single filaments of PP, N66 and PAN fibers. The surface of the used fibers after pull-out test was evaluated by optical microscope (OM). The effect of fiber types on the pull-out results of fiber/cement matrix at different ages of curing was also studied.

2. MATERIALS AND EXPERIMENTS

Cement used in this study was ordinary Portland cement type II. The type of used synthetic fibers and their properties are given in Table 1. Figures. 1-3 show the optical microscopic images of the longitudinal and cross-sectional surface of the fibers.

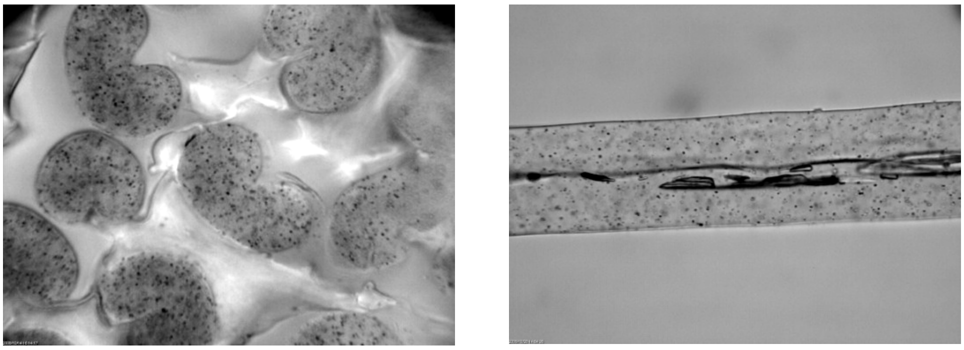
Table 1: Properties of fibers

Fiber type	Diameter (μm)	Density (gram/cm^3)	Tensile strength (MPa)
PP	25	0.91	326
N66	26	1.14	1122
PAN	40	1.19	344



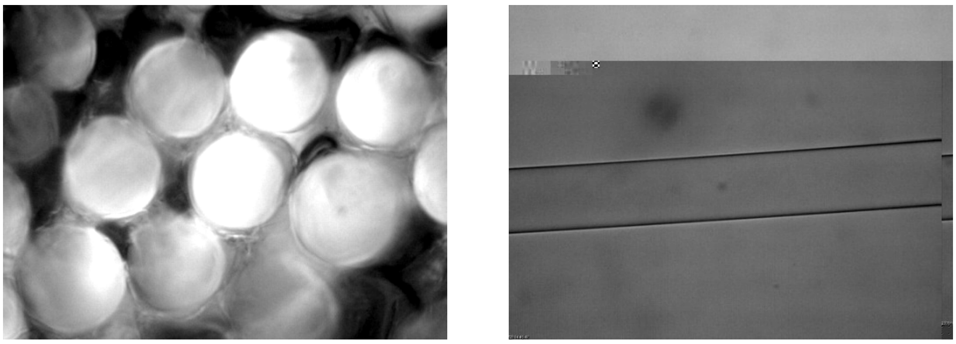
(a) (b)

Figure 1. Microscopic images of N66 fibers: a) Cross-sectional, b) Longitudinal view of fiber surface



(a) (b)

Figure 1. Microscopic images of PAN fibers:a) Cross-sectional, b) Longitudinal view of fiber surface



(a) (b)

Figure 1. Microscopic images of PP fibers: a) Cross-sectional, b) Longitudinal view of fiber surface

2.1. Specimen Preparation

Specimens for pull-out test were prepared by the equipment that has been designed and made for this research, as shown in Figure 4. The specimens were prepared with a matrix made by 0.5 of water to cement ratio. After demolding, specimens were subjected to cure in the condition of 23 ± 2°C and 100 ± 5% of relative humidity. Pull-out tests were carried out on specimens after 7, 14 and 28 days of curing. The embedded length for all series was 10mm long. Figure 5 shows the pull-out specimen before test.

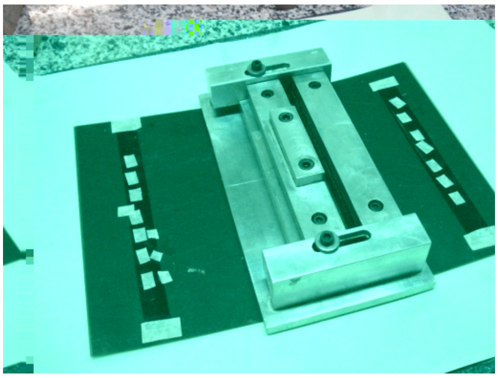


Figure 4. The equipment of pull-out sample preparation.

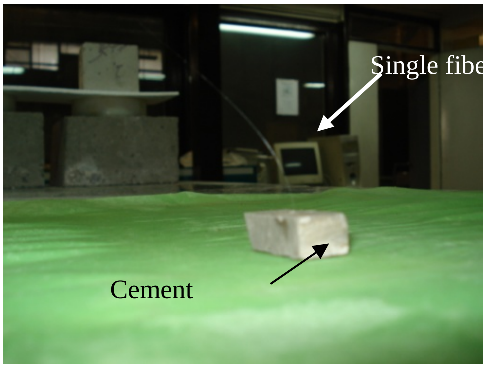


Figure 5. pull-out specimen after cutting

2.2. Pull-Out Test

To investigate the bonding characteristics, single fiber pull-out test was performed. The pull-out tests were carried out by an Instron testing machine (Tinius olsen) at the crosshead rate of 0.02 mm/s as shown if Figure 6. The schematic representation of the test set-up can be seen in Figure 7. The free length of single fiber was 10mm. Load–displacement data of pull-out process were obtained and plotted by computer.

Figure 6. single fiber pull-out test setup system

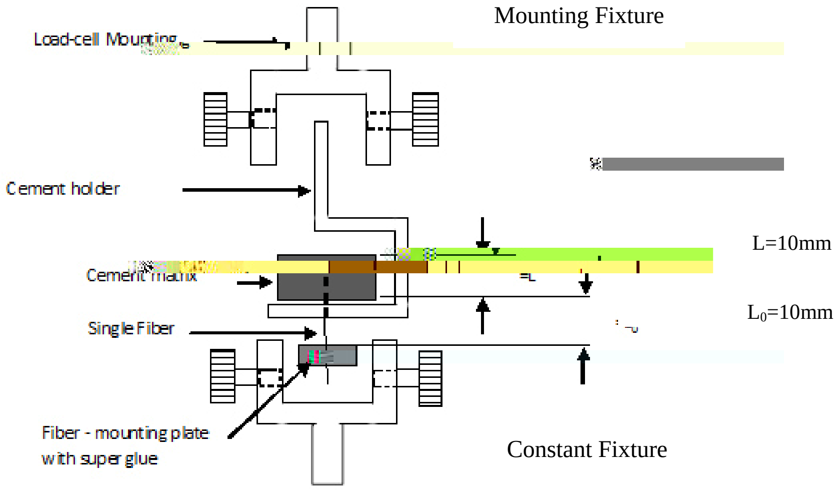


Figure 7. Schematic setup of single fiber pull-out test.

3. RESULTS AND DISCUSSION

3.1. Pull-Out Test Results

The pull-out behaviors of all series are illustrated by the load-extension curves in Figures. 8-10. In all series, it was observed that pull-out force is increased by increasing in fiber displacement to a maximum force. Thereafter, it decreases to zero level because of fiber slippage, pulling out or failure.

The analysis of N66 fibers load-displacement curves shows that there is no significant difference between pull-out load at 7 and 14 days. It can be said that the cement microstructure is not significantly changed during curing period from 7 to 14 days. The bonding strength in 28 days is remarkably higher than 7 and 14 days.

After complete debonding of specimens, N66 fiber begins to slip-out, so pull-out force is decreased.

Increasing the cement curing age of specimens containing PP fiber from 7 to 28 has a positive effect on pull-out load, as shown in Figure 9. Pull-out curves for PP specimens demonstrate that there is no significant difference between 7 and 14 days specimens. Pull-out curve at 28 days indicates that mechanical bonding between PP fiber and cement matrix is maximum. The pull-out curves show that the fiber/matrix bond strength gets close to fiber tensile strength.

In case of PAN fibers, increasing in curing period from 7 to 14 days has no significant effect on pull-out load. At 28 days of curing time, fiber failure happens during pull-out process because of higher bonding strength to cement matrix, as shown in Figure 10.

In all series, increasing curing ages from 7 to 28 days, improves bonding strength. In general, improvement in cement hydration results in decreasing of the porosity of hardened paste. The cement maturity has direct effects on the fiber/matrix bond properties.

In the transition zone more nucleation sites and open space are available in the around of the fiber surface. Based on this microstructure, CH layer in contact with the fibers grows much faster than the cement bulk. As reported by Chan [7], the transition zone is considerably weaker than the cement bulk due to large CH crystals and higher porosity. In other word, longer cement age and consequently the increase of hydration degree results in a decrease in the porosity and finally stronger fiber/cement interface.

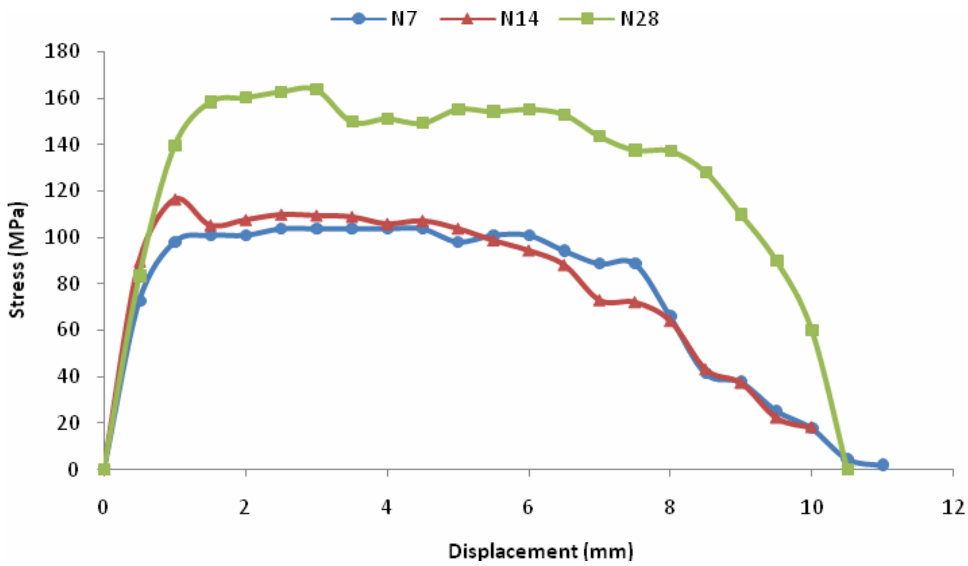


Figure 8. Pull-out behavior of N66 fiber at different cement ages

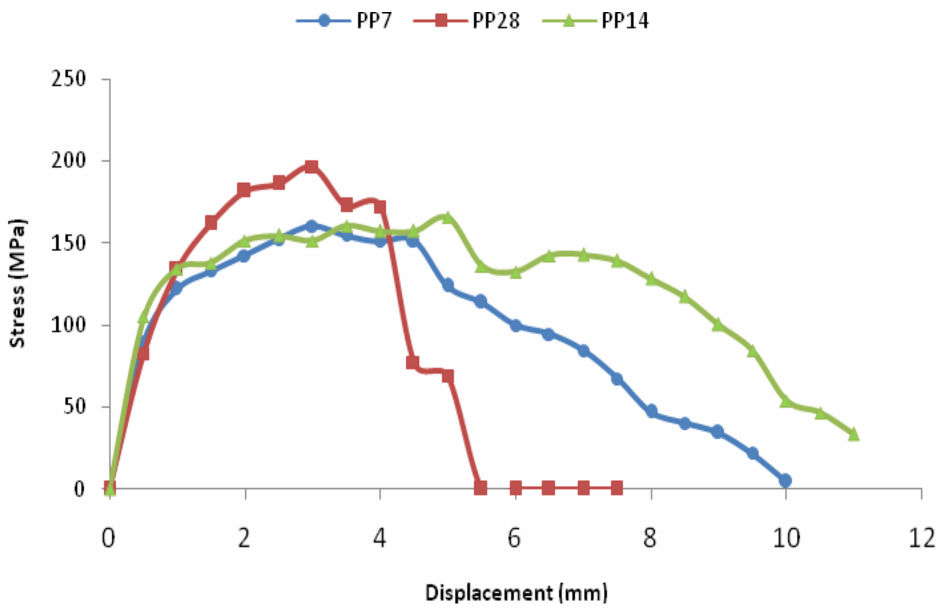


Figure 9. Pull-out behavior of PP fiber at different cement ages

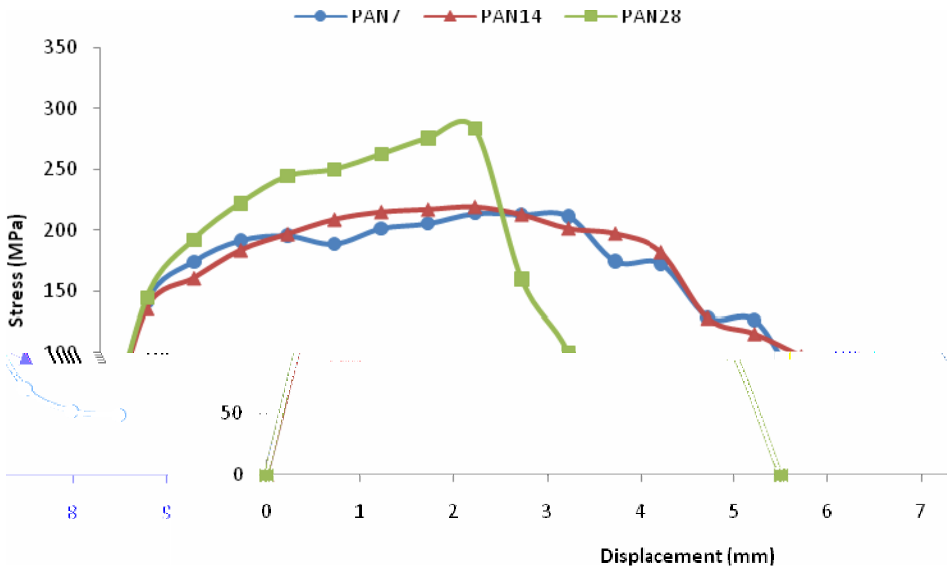


Figure 10. Pull-out behavior of PAN fiber at different cement ages

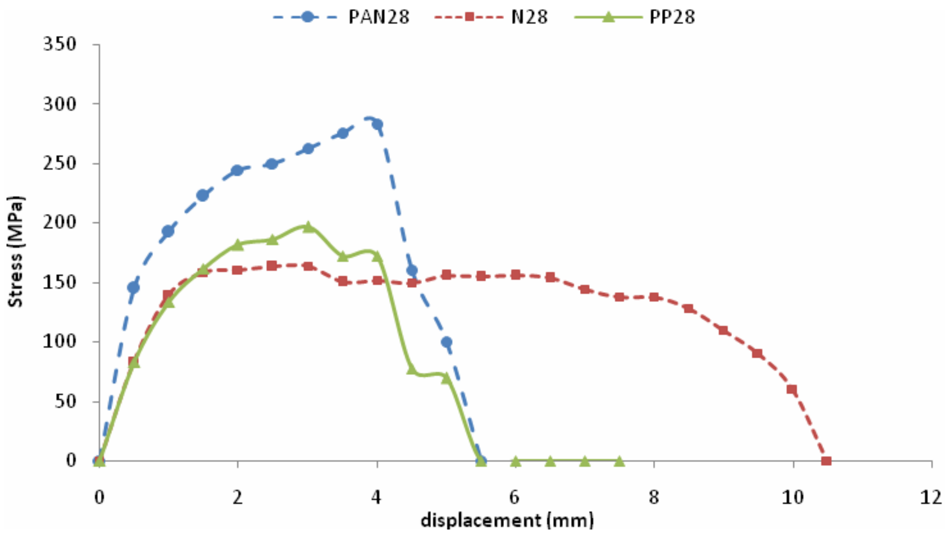


Figure 11. Pull-out curves of tested fiber at 28 days cement curing

Figure 11 shows pull-out curves of different fibers at 28 days of curing. It can be seen that PAN fibers showed higher pull-out strength in comparison to PP and N66 fibers. Figure 12 shows longitudinal image of pulled-out PAN fiber. It is evident that some cement particles are present on fiber surface. Due to the none-round shape of these fibers, during pull-out process, mechanical bonding can be performed because of interlocking effect to cement matrix. The special shape of cross-section indicates higher specific surface than round shape fibers. In other word, PAN fibers have much contacting surface to cement matrix which leads to increasing frictional resistance during pull-out. In the case of other fibers (PP and N66), the smooth surface and round shape of fibers causes less friction. However, in specimens containing PP, due to hydrophobic properties of PP and bleeding of cement paste, water is collected on the surface of the fiber. Therefore, calcium hydroxide (CH) coarse crystals are produced at the PP/cement interface. These crystals are enough big and coarse to deform PP surface. So, during pull-out, PP fibers interlock to these crystals.

3.2. Microscopic Analysis

The surfaces of pulled-out fibers were analyzed using optical microscopy. Figure 12 shows the chemical adhesion between cement bulk and PAN fibers. Due to the affinity between PAN fiber and cement paste which are both hydrophilic, chemical adhesion can be produced. These observations and the image of pulled-out PAN fibers indicate that PAN fibers have both chemical and mechanical bonding to cement paste.

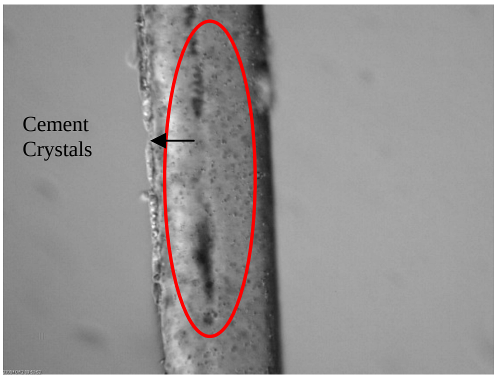


Figure 12. PAN fibers after pull-out process

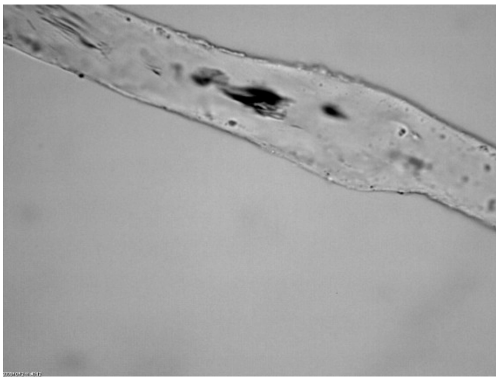


Figure 13. PP fibers after pull-out process

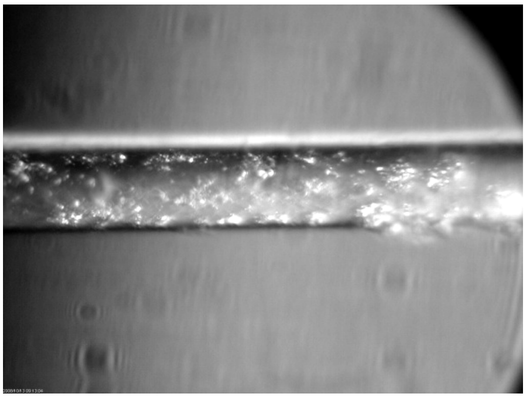


Figure 14. N66 fibers after pull-out process

Study on the pulled-out PP fibers from the cement matrix with optical microscope (OM) reveals the mechanical bonding of PP fiber to cement paste due to fiber deformation and elongation (Figure 13). Deformed points at fiber surface resist to fiber pull-out and thus, pull-out load are increased. Generally, the force and energy of fiber pull-out are increased with the presence of interlocking points between fibers and cement matrix, but this increase is limited by fiber tensile strength. In general, the friction bonding is changed with fiber deformation at fiber embedded length.

As shown in Figure14, the evaluation of N66 pulled-out fibers shows that cement particles attach to fiber surface. Based on this observation, it's found that N66 fibers have chemical bonding to cement matrix. Microscopic analysis also demonstrates that surface of N66 fibers have not been deformed.

4. DISCUSSION

Regarding to the pull-out behavior of fibers, it is resulted that N66 fiber has lower bonding strength to cement matrix compared to PP fibers. Microscopic analysis demonstrates that PP fiber has no chemical bonding to cement matrix while the presence of cement hydrates particles on the surface of N66 fibers is observed. Based on the observation, it is found that mechanical bonding is more effective than chemical bonding in fiber/cement matrixes.

PAN fibers have both mechanical and chemical bonding to cement matrix, due to their hydrophilic nature and cross section shape. Thus, the bonding strength for this fiber is higher than other studied fibers (Figure 11).

It should be noted that mechanical bonding in fiber/cement interface has an important role to enhance the mechanical performance of cement composite materials.

5. CONCLUSION

- The new pull-out sample preparation method was introduced in this research on the basis of single filament pull-out test.
- Increasing cement curing period from 7 to 28 improved bonding strength for all fibers. In general, the increase in the degree of hydration resulted in the decrease of hardened cement paste porosity.
- The imaging of all fibers surface showed that N66 and PAN fibers had chemical adhesion to cement matrix. The observation of propylene fiber surface confirmed its deformations.
- PAN fibers showed to have better bonding behavior to cement matrix because of mechanical and chemical adhesion. N66 fibers had weaker bonding action with cement paste in comparison to PAN and PP fibers.
- In spite of the lake of chemical adhesion between cement paste and PP fibers, high pull-out force was registered due to the mechanical interlocking.

REFERENCES

1. Pye, A. M., "*A Review of Asbestos Substitute Materials in Industrial APPlications*", Journal of Hazardous Materials, **1979**, Vol. 3, 125-147.
2. Kim, D. j., Naaman, A., El-Tawil E., S., "*Comparative Flexural Behavior of Four Fiber Reinforced Cementitious Composites*", Cement & Concrete Composites, Article in press, **2008**.

3. Peled, A., Zaguri, E., Marom, G., "*Bonding Characteristics of Multifilament Polymer Yarns and Cement Matrices*", Composites: Part A, **2008**, Vol. 39, 930-939.
4. Bentur, A., "*Role of Interfaces in Controlling Durability of Fiber-Reinforced Cements*", Journal of Materials in Civil Engineering, **2000**, Vol.12, No. 1, 21725.
5. Leung, C. K. Y., Ybanez, N., "*Pull-out of Inclined Flexible Fiber in Cementitious Composite*", Journal of Engineering Mechanics, **1997**, Vol. 123, No. 3.
6. Najm, H., Naaman, A.F., Chu, T. J., Robertson, R. E., "*Effects of Poly vinyl alcohol on Fiber Cement Interfaces. Part I: Bond Stress-Slip Response*", Advance Cement Base Materials, **1994,** Vol.1, 115-121.
7. Chan, Y. W., Li, V. C., "*Age Effect on the Characteristics of Fiber/Cement Interfacial Properties*", Journal of Materials Science, **1997**, Vol. 32, 5287-5292.