Flexural Behavior of Cementitious Composites Reinforced by Synthetic Fibers

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ABSTRACT

The application of fibers to reinforce cementitious materials is a well-known subject. At first, asbestos fibers are used in industrial process to produce fiber reinforced cement sheets. Thereafter, various types of synthetic fibers are produced and used as asbestos substitutes. The aim of the present work is to evaluate the effect of synthetic fibers on the flexural behavior of cementitious composites. In this study, the flexural strength of cement-based materials reinforced by three different types of synthetic fibers (polypropylene (PP), polyamide 66 (PA66) and acrylic (PAN)) is studied at various volume contents. It was found that although PAN and PA66 improve maximum flexural load borne by the cementitous composite before failure, the PAN fibers improves toughness of cementitous composites about 30% more than PP and PA66 fibers.

KEYWORDS

Flexural behavior, Fiber, Cementitious composites.

1. INTRODUCTION

The application of fibers for reinforcing cementitious materials is a well-known subject. Fibers are used in cement based materials to improve flexural behavior and/or control crack creation and propagation. They can bridge on cracks created in matrix under load to hinder composite fracture. At first, asbestos fibers were used in Hatschek process to produce fiber reinforced cement sheets. Because of great fiber strength and durability, high physical and chemical resistance, none-combustibility, resistance to weathering attack and cost effectiveness, asbestos has been used as a building material in various forms and styles during the last century to suit different needs. Despite all these properties, it can constitute a major health hazard to human safety [1-2]. Thereafter, various types of synthetic fibers have been produced and used as asbestos substitute.

The most frequently used reinforcement's fibers include organic fibers (acrylic, polyvinyl alcohol, polyolefin and sometimes, polyethylene- polypropylene copolymers), natural cellulose (hardwood and softwood pulps) and inorganic fibers (alkali-resistant glass and carbon) [3]. The type, geometry, distribution, orientation and volumetric concentration of fibers in the matrix are factors that affect the mechanical behavior of the composites [4].

Fiber reinforced concrete composites (FRCC) have the potential of exhibiting higher strength and ductility in comparison with unreinforced mortar or concrete, which fail in tension immediately after the formation of a single crack. The performance of FRCC can be improved to the point where it exhibits a deflection-hardening response in bending accompanied by multiple cracks after initial cracking [5].

Song p.s. et al. [6] investigated the application of nylon and polypropylene fibers for reinforcing concrete and found that the added fibers improved plain concrete properties including splitting tensile strength, first-crack strength and impact resistance. Nylon fibers have shown better performance in comparison with polypropylenes fibers.

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) [7].

A considerable amount of research has been carried out on the flexural behavior of FRCCs over the past four decades. The results have shown that low-volume

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contents of polypropylene fibers bring about statically significant improvements in flexural toughness. Alhozaimy et al. [8] reported that an additional amount of %0.1 polypropylene fibers had %44 increase in flexural toughness. Atushi K. [9], found synthetic fibers (PVA and PE) increase the ductility of the cement matrix, and bear higher performance of strength. It has been also shown that adding %1.5 wt of acrylic fibers increases the flexural resistance of the cement paste about %50 [10].

In this study, the effect of fiber types, volume contents and fibers geometry on performance of flexural strength of cement composite is investigated.

2. EXPERIMENTAL WORK

2.1. Mix Design

The matrix composed of ordinary Portland cement type II. The types of synthetic fibers used in this work and the fibers' properties are given in Table 1. Figures 1-3 show optical microscopic images of the fibers.

TABLE 1
PROPERTIES OF THE FIBERS

Fiber type	Diameter (µm)	Length (mm)	Density (gram/cm^3)	Tensile strength (MPa)
PP	25	5-6	0.91	326
PA66	26	5-6	1.14	1122
PAN	36	5-6	1.19	344

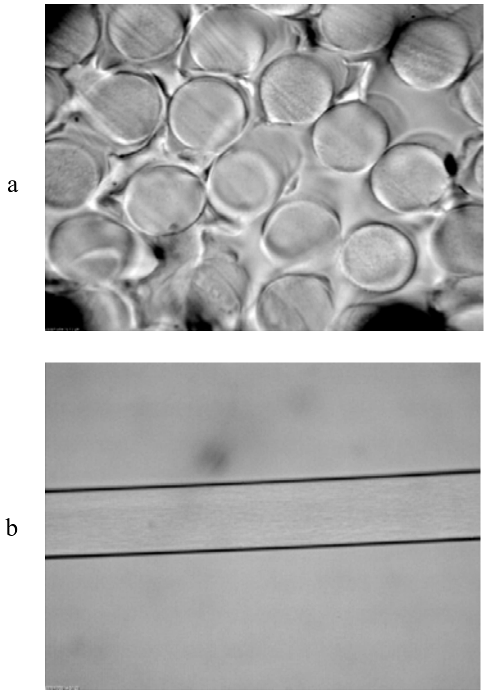

Figure 1: Microscopic pictures of PA66 fibers:
a) Cross-sectional, b) Longitudinal.

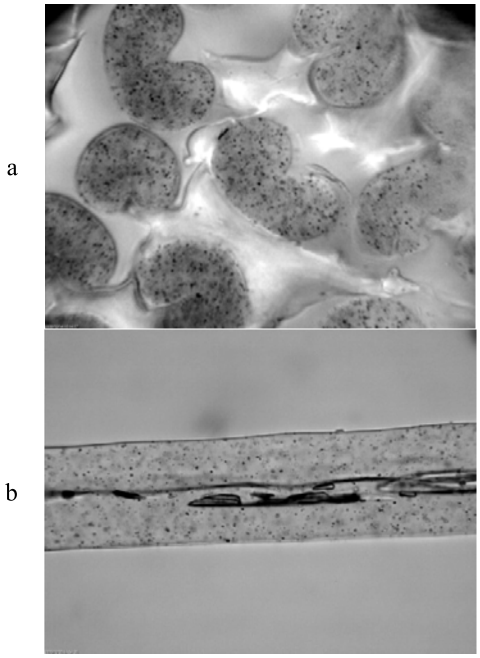

Figure 2: Microscopic pictures of PAN fibers:
a) Cross-sectional, b) Longitudinal.

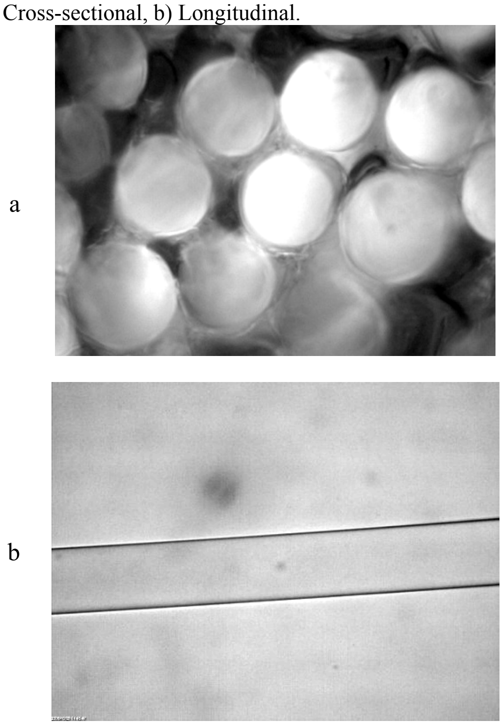

Figure 3: Microscopic pictures of PP fibers:
a) Cross-sectional, b) Longitudinal.

The fibers volume contents in cement matrix (cement paste) is shown in Table 2. Nine formulations were prepared with different amounts of the fiber contents [11-13]. All specimens were prepared from 150 gram of cement with water/cement ratio of 1. Three specimens for each mix design were prepared and cured in humidity chamber at temperature of 23±2°C and %100±5 of relative humidity for 28 days. After the curing time, the specimens were experimented for mechanical and physical performance by the three-point bending test on the basis of requirements of EN12647 standard.

TABLE 2
FIBERS VOLUME CONTENT CONTENTS

Fiber type	Volume content (%)
PP	0.25 - 0.5 - 0.75
PA66	0.5 - 1 - 1.5
PAN	0.5 - 1.5 - 2.5

2.2. Materials and Specimen Preparation

To produce prefabricated fiber cement sheets with maximized flexural strength, two different methods of Hatschek process and extrusion can be used. These methods permit the one to use higher fiber contents in cement composite to increase flexural strength. In this investigation, a sample preparation apparatus simulated to Hatschek process was designed and used (see Figs. 4 & 5). In this system, a dilute suspension of fiber and cement in water is used to ensure uniform dispersion of fibers in suspension. The suspension after casting will be dewatered to prepare a paste in the mould. To ensure uniform dispersion of fibers in the mould, the dewatering speed should be decreased and dilute suspension should be added gradually to the mould. The water to cement ratio in these process can varies from 1 to 4.

To produce dilute suspension, cement and water were mixed for about 2 min and the fibers were carefully dispersed in the mortar mixture and mixed for another 5–10 min. The cement paste mixture with the fibers was then transfused to the mould.

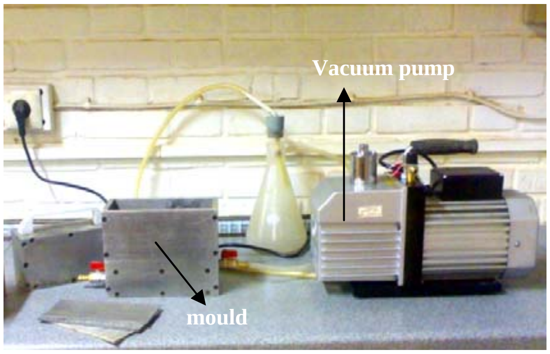

Figure 4: Instruments for preparing specimens.

Figure 5: Parts of specimen production equipment.

2.3. Flexural Strength Test

The dimension of the specimens was 280mm×80mm×8mm. The three-point bending test was carried out in accordance with EN12647. At least three specimens were used for each flexural strength test. The average curve of all tests are prepared and presented in this paper for better comparing.

The schematic of the test specimen and the test setup are shown in Fig. 6. The loading speed was 0.3 mm/min, and the clear span was 160 mm in these tests.

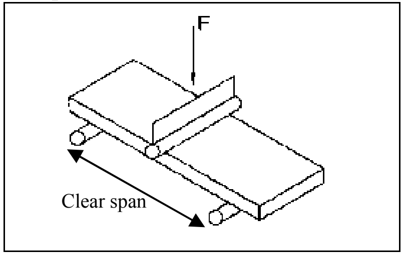

Figure 6: Schematic of three point bending test setup.

2.4. Alkali Resistance of Fibers

The next step for the study of fiber performance in cement paste is to assess fibers long-term durability. Fibers in cement paste are exposed to alkali attack because of increase in pH value due to hydration of Portland cement and calcium hydroxide generation. Some fibers are degraded in these conditions. So, the strength of composite will be decreased during the time. To evaluate the performance of the fibers in the alkali condition of cement paste, fibers were soaked in sodium hydration solution with pH of 12 for 28 and 56 days. Their tensile strengths were then tested.

3. RESULTS AND DISCUSSION

3.1. Fibers Tensile Strength

Results of tensile strength of the fibers after 28 and 56 days exposing to the alkali condition are shown in figures 7-9. The test showed that all used fibers have excellent alkali resistance.

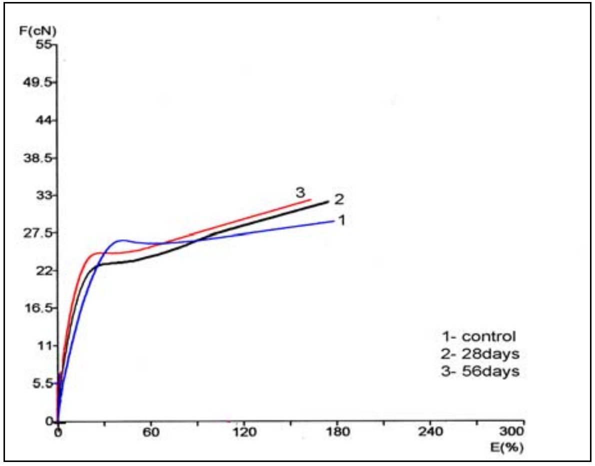

Figure 7: Load (cN)-extension (%) curves of PP fibers at different days of exposing to alkali condition.

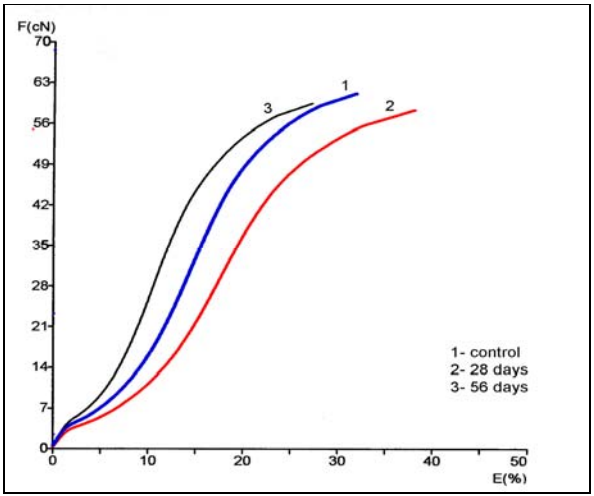

Figure 8: Load (cN)-extension (%) curves of PA66 fibers at different days of exposing to alkali condition.

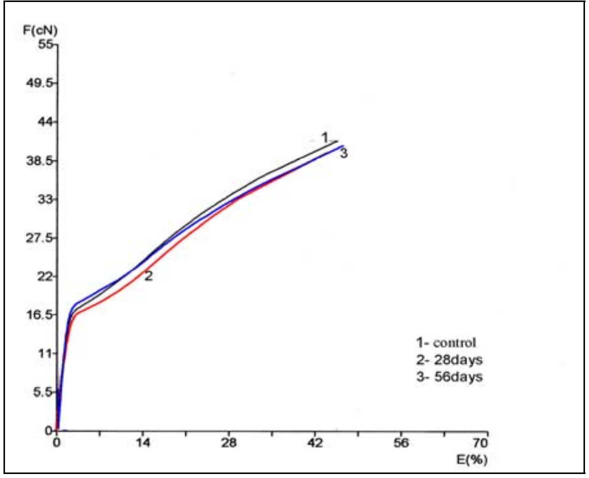

Figure 9: Load (cN)-extension (%) curves of PAN fibers at different days of exposing to alkali condition.

3.2. Flexural Test

The flexural behaviors of all the FRCCs are illustrated by the load-deflection curves in figures 10-12. Each load-deflection curve is the average of three specimen test results. As illustrated in Fig. 10, enhancing fiber volume content by the PA66 fibers from 0.5 to 2.5% increases the load bearing capacity of the composites. In the PAN fiber cementitious specimens, enhancing fibers' content to upper values had an inverse effect on the load bearing capacity, Fig. 11. It was attributed to migration of fibers toward upper suface of the cementitious sheets. In fact, these fibers do not contribute in load bearing. The maximum borne flexural load is decreased by increasing the fiber content from %1 to %1.5, but after cracking (i.e. the steep incline of the curve after maximum point) the composite containing further fibers shows better ductility.

The presence of fiber bundles and clumps in mix prepared with 1.5% volume content of PAN fibers is the main reason for lower flexural load. As illustrated in Fig. 12, an increase of the fiber volume content has no impact on load bearing capacity.

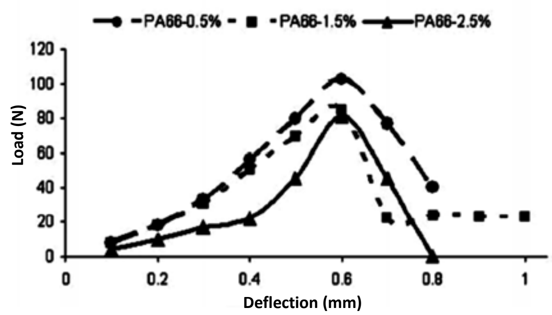

Figure 10: Load-deflection curves of specimens containing PA66 fibers at different fiber volume contents

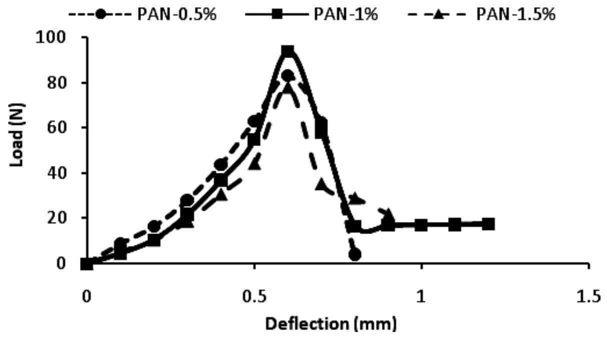

Figure 11: Load-deflection curves of specimens containing PAN fibers at different fiber volume contents

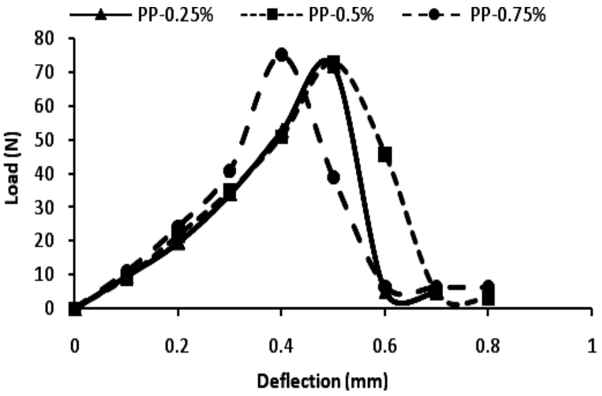

Figure 12: Load-deflection curves of specimens containing PP fibers at different fiber volume contents

To compare the flexural performance of different fibers, the load–deflection curves of used fibers at fiber volume content of 0.5% is shown in Fig. 13. It can be observed that the PAN and PA66 fiber reinforced cement specimens have the highest maximum flexural load. Furthermore, specimens containing PAN fibers show the highest load bearing behavior (toughness) considering the under curve surface area.

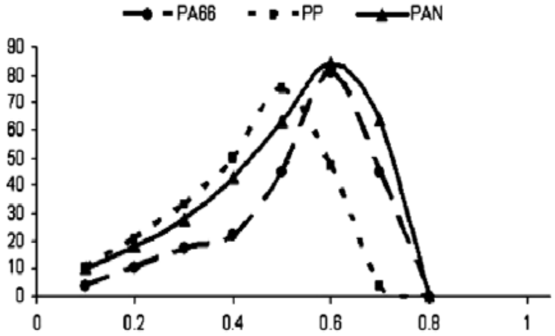

Figure 13: Load-deflection curves of specimens containing different fibers with 0.5% fiber volume contents

Because of the hydrophilic nature of PA66 fibers, they can be relatively better dispersed in water, and fiber volume content is increased in comparison with the PP and PAN fibers. PA66 fibers can properly bridge the cracks (Fig. 14). In this study, PA66 fibers volume content was extended even to 2.5 in the cement paste without causing serious fiber bundling and clumping.

Figure 14: PA66 fibers bridging crack.

In the case of using PP fibers, increase of the fiber content caused non-uniformity of fibers distribution in the cement paste during the production process, as reported by Jamshidi [11, 13]. The density of PP fibers is lower than water, so, they come up in the slurry in the mixing process and during the water suction process. So, scarce distribution of PP fibers in the whole matrix leads to a decrease in the load bearing capacity of the composite. Although the PAN fibers showed better distribution in cement paste than PP, increase in the fiber volume content more than %1 caused its bundling, and reduced the effectiveness of the its reinforcement and the maximum flexural load.

The aggregation of fibers at the surface of specimens containing PP and PAN fibers is shown in Fig. 15 and Fig. 16, respectively.

Fig. 15: Aggregation of PP fibers on matrix surface

Figure 16: Aggregation of PAN fibers on matrix surface.

According to the load-deflection curves (Fig. 10 to Fig. 12), due to the low modulus of the used synthetic fibers, the reinforced cement specimens are fractured with the first crack. In fact, the reinforcement by low-modulus fibers enhances mainly the ductility of the cement composites, but not their strength and results in a strain softening or elastic–plastic behavior. The major effect of the fibers in the cement matrices is deflection-hardening in the post-cracking zone. Generally, enhancing fiber volume content can lead to improving deflection-hardening behavior while it causes non-uniformity in mixing during sample preparation.

3.3. Evaluation of Toughness

It is very important to evaluate the energy absorption capacity (toughness) of fiber reinforced cement materials subjected to dynamics loads, such as seismic and impact load. Toughness is defined as the area under the load-deflection curves. As shown in Fig. 7 to Fig. 9, the area under the load-deflection curves of PA66 and PAN fibers is greater than PP fibers', which means a higher toughness value. Also, with increasing in fiber volume content in specimens as shown in figures 9-11, toughness increases.

Adhesion of the PAN and PA66 fibers to cement paste is one of the factors that are responsible for the efficiency of load transfer. The pullout behavior of fibers when matrix cracking represents the flexural strength of the composites, and the pullout work represents the energy consumed in the failure process or the composite's toughness. As shown in Figs. 17 and 18, cement particles attached to the fibers surface justify the presence of chemical adhesion between PAN and PA66 fibers and cement paste, particularly PA66 fibers. Moreover, the specific cross-section of PAN fibers causes interlocking with cement matrix and helps fibers against pulling out from cement matrix in failure processing. The cross-sections of PA66 and PP fibers unlike PAN fibers are round, as shown in Fig. 1a and Fig. 3a. Thus, mechanical bonding (i.e. interlocking) can be decreased between these fibers and the cement matrix [12]. The composites containing PAN fibers show better physical-mechanical performance in the flexural reaction.

Figure 17: PA66 fibers.

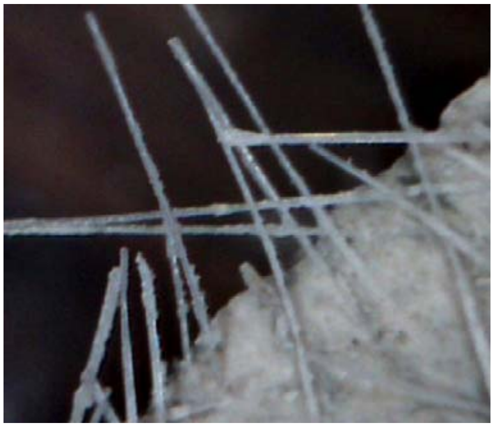

Figure 18: PAN fibers.

4. CONCLUSION

It can be concluded that:

- All chosen fibers were alkali resistant. Although, usually nylon fibers degrade in the alkali condition but the PA66 fiber used in this work was tire cord grade and alkali resistant. The fibers were proper for utilization in the cement matrices;
- Short-staple fibers randomly distributed, improved the flexural strength and ductility of cement paste, but did not change their failure mode at deflection-hardening in post-cracking zone. With the same fiber volume content, the flexural behavior of the PAN fibers reinforced cement was better than PA66 and PP fibers. The reinforcement with PP fibers resulted in lower flexural strength composites in comparison to two other fibers;
- The surface area under load (N)-extension (mm) curves is considered as toughness of composites. On the basis of results, The PAN fibers reinforced cement composites showed higher toughness (about 30%), because of the greater area under load-deflection curve than PP fiber and PA66 reinforced cement composites. Increase in fiber volume content usually improves the toughness

behavior of the cement composites, albeit under critical fiber volume contents;

– Synthetic fibers acted very well in crack bridging of cement pastes under flexural load;

– The adhesion of the fibers to the cement matrices and the interfacial transition zone (ITZ) played important roles in maximum borne flexural load and the energy absorption of the composites.

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