CONCRETE WITH ENHANCED DUCTILITY USING STRUCTURAL MICROFIBERS

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Abstract

Concrete, one of the most widely used construction materials in the world, is typically composed of portland cement; water; aggregates such as sand, gravel, or crushed stone; and admixtures. Unlike steel, concrete is a quasi-brittle material. For design purposes, the tensile strength of concrete is negligible, since it is relatively weak in tension. Reinforcing steel is added to concrete for this purpose because steel is relatively strong in tension and has greater ductility. In recent years, materials like fiber-reinforced cementitious composites have been explored and developed. Many types of fibers with varying sizes have been examined in concrete in hopes of developing more ductile cementitious materials than traditional concrete. The components of these fiber-reinforced cementitious materials are similar to traditional concrete, except no coarse aggregates are used and air entrainment is not necessary. And, like traditional concrete, fiber-reinforced cementitious materials are cost effective. Numerous large-scale potential applications exist, including buildings, bridges, airports, culverts, dams, and projects involving repair or rehabilitation work.

In this paper, the authors present the results of a fiber-reinforced cementitious composite that has been developed over time, and based on work reported in the literature with modifications based on experimentation of mix designs using high-performance polyvinyl acetate (PVA) microfibers. Cube test specimens were cast and tested in compression and indirect tension. In addition, a large-chamber scanning electron microscope examined fiber crack bridging of post-failed cube specimens that were loaded in indirect tension (split cube tests). Results showed that test specimens of concrete reinforced with PVA microfibers exhibited a decrease in compressive strength, but a significant increase in indirect tensile strength, and have more ductility than specimens not containing the fibers, such as more traditional types of concrete.

Introduction

In the last few decades, growing interest has developed in using fibers in ready-mixed concrete, precast concrete, and shotcrete. Fibers made from steel, plastic, glass, wood, and other materials have been used in concrete. Fibers are typically added to concrete mixes in low-volume dosages, often at rates less than 1.0%, for purposes of reducing plastic shrinkage cracking [1]. However, fibers do not affect the free shrinkage of concrete, but, given high enough dosages, fibers can increase resistance to cracking as well as decrease the size of the crack widths [2]. Generally, fiber-reinforced concrete is grouped into two classes: thin-sheet products and bulk structure products. Fiber fraction volumes further determine subclassifications and uses for each class, with low-volume fiber fractions (<1%) primarily serving to resist plastic shrinkage and high-volume fiber fractions (2>-10%) serving to provide additional or secondary reinforcement to main reinforcing steel. High volumes (up to 20% steel fibers) have been demonstrated to significantly improve all strength properties. Fiber-reinforced concrete has become synonymous with various steel fiber reinforcements. However, the addition of steel fibers increases weight. Perhaps concrete in the form of a cementitious composite could be developed that utilizes nonferrous structural fibers. This material would capitalize on the additional strength of fibers, while providing a significantly lighter composite material. One such possibility is the use of synthetic polymer fibers.

Synthetic fibers are the result of research and development in the petrochemical and textile industries. Synthetic fibers that have been used in portland cement concrete include acrylic, aramid, carbon, nylon, polyester, polyethylene, and polypropylene. One problem with synthetic fibers is their ability to disperse and distribute evenly in the composite, providing a compatible and continuous bond between the fibers and the cementitious paste matrix. Polypropylene fibers are commonly used as a fiber in portland cement concrete, since the fibers are chemically inert, hydrophobic, and lightweight. Fibers of this type are generally added at a rate of 0.1% by volume of concrete. Polypropylene fibers can reduce plastic shrinkage cracking and help reduce concrete spalling.

Figure 1 shows how, for many years, researchers have attempted to produce concrete that is more ductile in behavior [3, 4]. In most cases, ductile concrete has been achieved using fiber reinforcement. Concrete with synthetic polymer fibers, such polypropylene microfibers, was the result of this development effort. This material has demonstrated impressive ductile behavior. Bending can be achieved with a high level of inelastic deformation resulting from the development of numerous microcracks with limited crack widths. This is in sharp contrast to traditional concrete, where a single point of failure (crack with a large crack width) develops from excessive bending. Research and development by Li [5, 6] has produced a cementitious material using these types of fibers, which has greater ductility than traditional types of concrete. This material has been used in a number of projects worldwide and was proposed for many others [7]. The largest use of this material to date has been as a 5-mm thick topcoat on the Mihara Bridge in Hokkaido, Japan. Domestically, the Michigan Department of Transportation has used this material for surface repair projects and as a flex joint for replacement of a steel expansion joint on a bridge deck crossing over I-94 in Ypsilanti, Michigan.

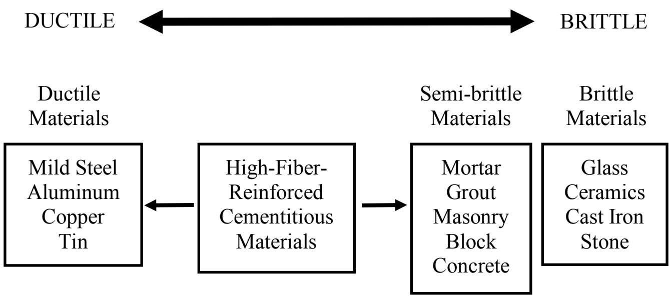

Figure 1. Range of Ductile-to-Brittle Behavior of Materials

In this current study, the authors examined a type of concrete reinforced with PVA microfibers and compared it with the same concrete without fibers. The project was conducted in two phases: first to cast cubes in order to compare compressive and indirect tensile strengths of the concrete with and without PVA microfibers, and then to use a large-chamber, scanning electron microscope to examine PVA microfiber bridging across concrete cracks of cube specimens that were loaded to failure in indirect tension (split cube tests).

Polyvinyl Alcohol Microfibers

Polyvinyl alcohol (PVA) microfibers at the molecular level consist of repeated structural units of $-[-CH_2-CH(OH)-]_n-$. Using PVA microfibers as a reinforcement material leads to many benefits. Apart from being economical, the PVA microfiber reinforcement improves the quality of concrete by making it fatigue and corrosion resistant. Polyvinyl acetate is the starting material in the manufacturing of polyvinyl alcohol (PVA). PVA is hydrolyzed by treating it with an alcoholic solution in the presence of an aqueous acid or alkali. OH groups present in PVA can form hydrogen bonds between the fibers and the cement matrix. The resulting surface bonding helps in bridging across cracks. Figure 2 shows that the tensile strength of PVA fibers is significantly higher than mild steel rebar used in reinforced concrete, which also contributes to improved bridging performance when cracks develop and propagate.

Figure 2. KURALON Ultra-High-Performance Nycon PVA Microfibers

Comparative Concrete Batch Designs

Figure 3 shows the two batches of concrete that were cast: the first was the baseline concrete containing no microfibers, and the second was reinforced with 8-mm PVA microfibers added at a volume fraction of 2.2%. All other components were measured and kept identical to the baseline concrete for comparative purposes. Portland cement type III was used since it is finer than type I. Super plasticizer Glenium 3000 NS, a high-range water reducing admixture, was used to increase the workability of concrete. The resulting mix was prepared using a water-to-cement ratio of 0.59. Table 1 summarizes the mix design used to establish the baseline concrete cube tests, where the amount of each component is given in kilograms per cubic meter of concrete cast.

Table 1. Concrete Mix Proportions

Component	Amount (kg/m^3)
Portland cement (type III)	605.5
Fine aggregate (sand)	484.4
Fly ash (type C)	726.6
Water	353.2
Super plasticizer (Glenium 3000 NS)	8.6

Figure 3. Incorporation of PVA Microfibers in Concrete

Experimental Tests

All other mix proportions were the same between the two concrete batches. Each batch produced a total of 48 specimens, which were 50x50x50 mm cubes. From each batch, 24 cubes were tested in compression, while the other 24 cubes were tested in indirect tension (split cube test). For the baseline concrete, four cubes each were tested in compression at 1, 3, 7, 14, 21, and 28 days to determine the compressive strength gain as a function of curing time. The same was performed for the concrete reinforced with PVA microfibers. Also for the baseline concrete, four cubes each were tested in indirect tension (split cube test) at 1, 3, 7, 14, 21, and 28 days to determine the indirect tensile strength gain as a function of curing time. Figure 4 shows how this was also done for the concrete reinforced with PVA microfibers. Indirect tensile strength (split cube tensile strength) was calculated using Equation (1):

$$\sigma_{sp} = 0.519\, P / S^2 \qquad (1)$$

where, P is the failure load in Newtons and S is the length of the side in millimeters of the concrete cube [8].

A large-chamber, scanning electron microscope (LC-SEM) was used for imaging the cubes with fibers. These cubes were first tested in indirect tension (split cube test) and then examined using the LC-SEM. A vertical crack formed during the test, and the PVA microfibers were observed to be bridging across the cracks. To better demonstrate this bridging, imaging was done using an LC-SEM. LC-SEM is a scanning electron microscope, with a magnification power of up to 300,000x, used for high-resolution imaging. This instrument accommodates large samples without the need to cut them into small pieces, which damages the specimens. The images generated have a resolution greater than 10 nm. This instrument helped to better understand the nature of fiber bridging that occurred across the concrete cracks that developed. Figure 5 shows the LC-SEM available at the WKU NOVA Center, one of only two in the world.

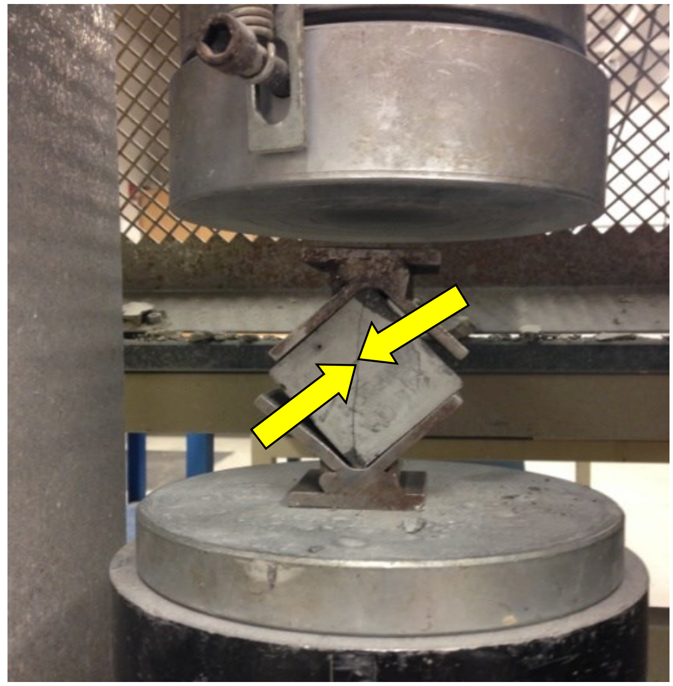

Figure 4. Vertical Crack in Split Tensile Strength Test Cube

Figure 5. Large-Chamber Scanning Electron Microscope at WKU NOVA Center

Test Results

Figure 6 shows the average compressive strength and the age of the concrete cubes with and without fibers. The concrete batch without fibers is referred to as the baseline concrete, while the other batch is referred to as the concrete with PVA fibers. Not including day 1 results, the fiber-reinforced concrete cubes exhibited an average of 26.7% less compressive strength than the cubes without fibers. The fibers in the composite cause the formation of voids in the presence of filling material (sand). This results in the improper packing of the concrete, thereby decreasing the compressive strength of the test specimen [9].

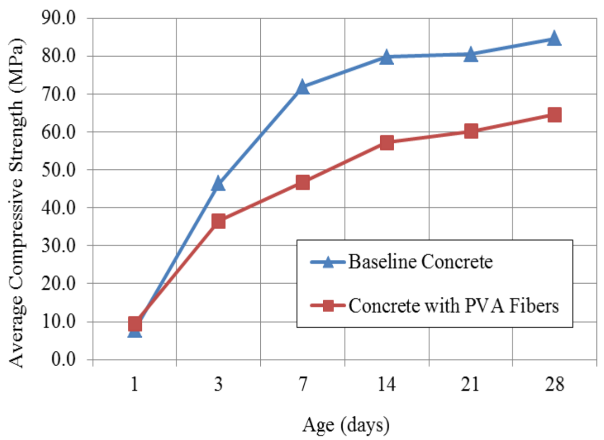

Figure 6. Compressive Strength at Various Ages

Figure 7 shows the average indirect tensile strength (split cube tensile strength) and the age of the concrete cubes with and without fibers. The fiber-reinforced concrete cubes exhibited an average of 57.4% more indirect tensile strength than the cubes without fibers.

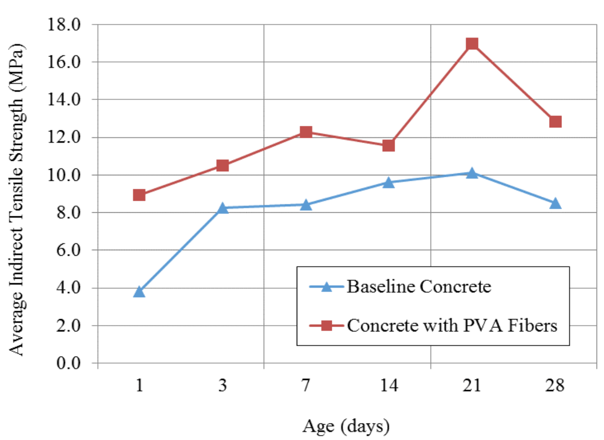

Figure 7. Indirect Tensile Strength at Various Ages

SEM images of concrete cubes tested for split tensile strength were collected. Figure 8 shows the fibers bridging across the crack. It also shows that the fibers are pulled between the crack and that they are under stress. When a crack is formed in PVA fiber-reinforced concrete, the fibers act as bridges or stitching between the cracks, which helps to prevent or limit the formation of macrocracks. These fibers undergo tension as they are pulled in between the cracks. PVA microfiber pullout from the cementitious matrix was not observed.

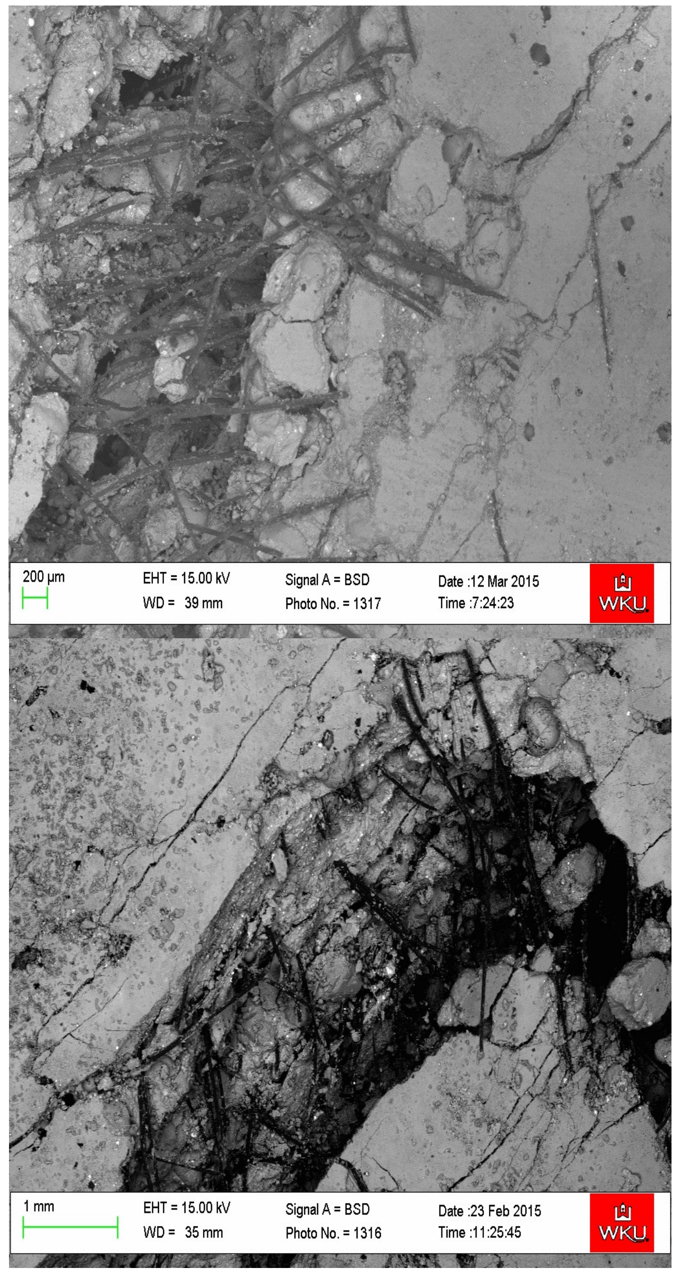

Figure 8. SEM Images of Fibers Bridging Cracks in the Concrete

Summary and Conclusion

In this study, the authors examined the effect of PVA fiber loading of 2.2% by volume on the mechanical properties of concrete. Compressive strength and indirect tensile strength testing was done for both baseline and PVA microfiber-reinforced concrete cubes. When compressive strength was examined as a function of curing time, the concrete cubes with PVA microfiber reinforcement exhibited 26.7% less compressive strength than the baseline concrete cubes, whereas when indirect tensile strength was examined as a function of curing time, the concrete cubes with PVA microfiber reinforcement exhibited 57.4% more indirect tensile strength than the baseline concrete cubes. An increase in the indirect tensile strength shows that the concrete has gained ductility. SEM imaging of the samples was done to observe fiber bridging across the concrete cracks. Based on the images collected, all cracks observed were shown to have PVA microfibers bridging across the crack widths. PVA microfiber pullout from the cementitious matrix was not observed.

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