Fiber Reinforced Concrete Using Recycled Carpet Industrial Waste and Its Potential Use in Highway Construction

Youjiang Wang
School of Textile & Fiber Engineering

Baik-Soon Cho and Abdul-Hamid Zureick
School of Civil Engineering

Georgia Institute of Technology
Atlanta, GA 30332

ABSTRACT

The U.S. carpet industry consumes about 1.2 million tons of fibers annually and about 70% of the carpet produced is for replacement. The waste generated by the industry and from used carpet is estimated at about 2 million tons per year, most of which is disposed in landfills at present. A study was carried out to study the use of recycled fibers from the carpet industry waste for reinforcement of concrete at a 2% volume fraction. Compressive and flexural tests for strengths and toughness were conducted, and significant increase in shatter resistance, energy absorption, and ductility were observed. This paper reports on the experimental program and compares the effectiveness of such recycled fibers with that using virgin polypropylene fibers specially made for fiber reinforced concrete (FRC). The paper also discusses the benefits of using such FRC to replace conventional concrete in highway construction, including increased service life and reliability.

INTRODUCTION

Concrete is not only the most heavily used man-made material in the world but also a widely used material for construction of highway facilities. Concrete is durable, inexpensive, readily molded into complicated shapes, and has adequate compressive strength and stiffness. However, concrete has low tensile strength, low ductility, and low energy absorption. Due to its lack of tensile strength, concrete is often reinforced with steel reinforcing bars (re-bars) in structural applications. However, steel re-bar corrosion has contributed to the decay of reinforced concrete structures. Fiber reinforced concrete (FRC) is often made by adding a small fraction (usually below 2% by volume) of short fibers to the concrete mix during mixing. After extensive studies in the last three decades, it is now beyond doubt that such fiber reinforcement can significantly improve the tensile properties of concrete. Orders of magnitude increases in toughness (energy absorption) over plain concrete is commonly observed. Fiber reinforcement can also improve the fatigue strength and reduce the drying shrinkage of concrete.
Fiber reinforced concrete is currently being used in many applications including buildings, highway overlays, bridges, and airport runways [1-3]. In load bearing applications it is generally used along with traditional steel reinforcement. By using FRC instead of conventional concrete, section thickness can be reduced and cracking can be effectively controlled, resulting in more lightweight structures with longer expected life.

This paper reports on an experimental program to evaluate the effectiveness of using recycled fibers from carpet waste for concrete reinforcement. The results suggest that using such recycled fibers in highway construction would not only improve the reliability and life of the highways, it but also could reduce the landfill spaces needed to dispose the waste material.

PROSPECT OF USING RECYCLED FIBERS IN HIGHWAY CONSTRUCTION

The decay in infrastructure has become a national concern recently. The main cause of this crisis is the deterioration of the material used in the original construction and in subsequent repairs. Many of the interstate highways in United States were built in the 1950s, with a design life of 20 years. According to the Federal Highway Administration, there are about 1.2 million miles of major highways in the United States, or about 17,000 square miles in area. A typical highway section consists of asphalt, concrete, and aggregate layers on compacted soil. After decades in service, signs of aging and deterioration, such as cracking, spalling, and scaling are commonplace. Clearly, there is an urgent need for development of advanced construction materials with better strength and toughness for new constructions as well as for repair of damaged structures.

In the process of FRC fracture, fibers bridging the cracks in the matrix can provide resistance to crack propagation and crack opening before being pulled out or stressed to rupture, as illustrated in Figure 1. By replacing the concrete layer with FRC in highway construction, the fibers will tend to hold concrete pieces together after cracking, preventing or delaying further deterioration. The reduction in maintenance and repair costs and interruptions could have significant economical impact. Fibers used in FRC include steel, alkali-resistant glass, and various synthetic fibers, most notably polypropylene. Recycled synthetic fibers such as those from

![Figure 1. Schematic Illustration of Fiber Bridging Action in FRC](image)
textile industry waste offer low cost alternatives for concrete reinforcement.

One type of recycled fiber comes from the carpet industry and from used carpets. The U.S. carpet industry produces about 1 billion m² of carpet and consumes about 1 million tons of synthetic fibers per year. About 70% of the carpet produced is for replacement of used carpet, which translates into about 1.7 million tons of used carpet for disposal. In the Dalton, Georgia area, where many carpet manufacturers are located, over 40,000 tons of carpet waste (including lint) has to be disposed of each year. Finding available landfill space has become increasingly difficult. This problem not only causes environmental concerns, but also has an adverse effect on the U.S. carpet industry, one of the largest employers and economical sectors in the State of Georgia and in several other states.

A carpet typically consists of two layers of backing (usually polypropylene), joined by CaCO₃ filled styrene-butadiene latex rubber (SBR), and face fibers (majority being nylon 6 and nylon 66) tufted into the primary backing, as illustrated in Figure 2. Most of the carpet industry waste is selvage trim, seams, and lint. Thus the major components of the carpet waste are polypropylene, nylon 6, nylon 66, and SBR. Other materials—polyester, wool, jute, acrylic, etc., form a relatively small portion of the waste. Some waste is generated before the application of SBR. Such waste is termed soft waste, most of which is reused. The waste containing the SBR (termed hard waste) forms the major part of the waste going into the landfills.

The carpet industry is recycling much of its soft waste. There are some R&D activities undertaken by major carpet fiber producers on recycling of carpet waste including hard waste and used carpet. It seems that a major effort has been placed on the complete separation of the waste and then reuse of each component.

As to be discussed in the following sections, concrete reinforced with recycled fibers from hard carpet waste was studied. Improved shatter resistance in compression and pseudo ductile failure in flexure were observed with such fiber reinforcement. It suggests that using recycled carpet in highway construction could be a very cost-effective way to improve the durability and performance of our highway system, and to reduce the needs for landfill spaces.
EXPERIMENTAL PROGRAM

*Materials:* The concrete matrix consisted of Type I Portland cement, river sand, crushed granite aggregate (maximum size=10 mm), and water. The weight ratios were 1.0 (cement)/0.35 (water)/0.85 (sand)/0.61 (aggregate). 2.5% (by weight) of superplasticizer relative to the water weight was also added to improve the workability.

Recycled carpet waste fiber used was from hard carpet waste, disassembled mechanically by the Crown America, Inc. of Dalton, Ga. After disassembling, surface yarns (nylon) and some backing fibers (polypropylene) were collected. This collection is referred to as Type I waste fiber and had a typical length range between 12 to 25 mm. The disassembled waste after removal of Type I fiber is referred to as Type II, which contained backing fibers, SBR coated face yarns, and SBR particles. An analysis of Type II fiber indicated that the fiber length was about 3 to 25 mm and that about one third by weight was actually fiber, the other two thirds being CaCO$_3$ filled SBR. A photograph of Type II fibers is given in Figure 3.

Fiber volume fractions for the waste fibers were kept at 2%. Only the actual fiber portion was included for calculating fiber volume fractions for Type II waste fiber reinforced concrete.

FiberMesh® virgin polypropylene fiber at 0.5% volume fraction was also included in this study for comparison purposes. The fiber length was 19 mm.

*Sample Preparation:* A drum mixer was used for mixing. The freshly mixed concrete was filled into plastic molds, and then stored in a saturated curing room (100% RH). For each mix, 6 beams (102×102×356 mm) and at least 14 cylinders (76 mm in diameter and 152 mm in height) were prepared.
### TABLE I: Compressive and Flexural Test Results

<table>
<thead>
<tr>
<th>Fiber in FRC Mix</th>
<th>$V_f$</th>
<th>Compressive strength 1 day</th>
<th>28 days</th>
<th>Flexure Test at 28 days Strength</th>
<th>Toughness</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>%</td>
<td>MPa (CV%)</td>
<td>MPa (CV%)</td>
<td>MPa (CV%)</td>
<td>$I_s$ (%)</td>
</tr>
<tr>
<td>Concrete control</td>
<td>0</td>
<td>20.9 (4.9)</td>
<td>52.6 (3.1)</td>
<td>4.6 (4.0)</td>
<td>1.0</td>
</tr>
<tr>
<td>Fiber Mesh PP</td>
<td>0.5</td>
<td>24.2 (3.7)</td>
<td>52.2 (1.4)</td>
<td>4.6 (3.1)</td>
<td>2.6</td>
</tr>
<tr>
<td>Type I waste fiber</td>
<td>2.0</td>
<td>20.9 (5.7)</td>
<td>39.7 (7.4)</td>
<td>4.7 (2.3)</td>
<td>3.3</td>
</tr>
<tr>
<td>Type II waste fiber</td>
<td>2.0</td>
<td>18.6 (7.6)</td>
<td>40.7 (7.4)</td>
<td>4.4 (4.3)</td>
<td>3.5</td>
</tr>
</tbody>
</table>

*Figure 5. Typical Flexural Test Curves*

*Figure 6. Photograph of an FRC Beam (with polypropylene fiber) in Flexural Test After Matrix Cracking Showing Fibers Bridging the Crack*
Test Configurations: Four point flexural test and cylinder compressive test were illustrated schematically in Figure 4. These tests were performed on a hydraulic testing machine in general accordance with ASTM C-78, C-1018 and ASTM C-39. A 200 kN load cell and a linear variable differential transformer (LVDT) were used to measure the load and displacement respectively, and the data was recorded by a data acquisition system for analysis. The loading rate was 0.25 mm/minute for both tests.

The 28 day flexural test of 102x102x356 mm beams was performed at a span length of 305 mm. Beams were turned 90° from the casting position to ensure even loading. Beam deformation was measured at the center point with an LVDT. Compression cylinders of 76 mm in diameter and 152 mm in height were tested at specimen ages of 1 day and 28 days. The specimens were first capped with a sulfur-based capping compound to allow uniform loading.

RESULTS AND DISCUSSION

The results for compression and flexural tests of various mixes are given in Table I. Six or seven specimens were tested for each setup.

In the one day compressive test, similar strength values were observed for plain concrete and various FRCs. It appeared that the 28 day compressive strengths of carpet waste FRCs were lower than that of plain concrete. However, the plain concrete specimens failed in a brittle manner and shattered into pieces. In contrast, all the FRC samples after reaching the peak load could still remain as an integral piece, with fibers holding the concrete matrices tightly together.

The flexural strengths of all mixes tested were essentially the same and the standard deviations were low. Figure 5 shows the typical load versus displacement curves for the flexural test. The plain concrete samples broke into two pieces once the peak load was reached, with very little energy absorption. The FRC specimens, on the other hand, exhibited a pseudo ductile behavior.
A photograph of an FRC specimen containing virgin polypropylene fibers during the flexural test is shown in Figure 6, in which fibers bridging the beam crack can be seen. Similar post matrix crack behavior was also observed for other FRCs. For the FRC samples tested, the load carrying capacity was as high as over 40% of the flexural strength even when the beam deflection had exceeded several times the cracking deflection, and the crack had opened to several millimeters in width. Because of the fiber bridging mechanism, the energy absorption during flexural failure was significantly higher than that for plain concrete. One method of characterizing the energy absorbing ability, or toughness, of FRC is to calculate the toughness indices, as proposed in ASTM C1018. The index is the area under the flexural test curve up to a specified displacement ($\delta$) normalized by the area up to matrix cracking. $\delta$ equal to three times the cracking deflection ($\delta_c$) is used for $I_5$ and $\delta=10.5 \delta_c$ for $I_{20}$. $I_5$ and $I_{20}$ values for the beams tested are included in Table 1. These indices indicate the energy absorption of FRC compared with a brittle material such as concrete (toughness index=1.0) for the deformation range specified. Since cracking, spalling, and scaling types of deterioration are related to the brittleness of concrete, using FRC in highway construction could make the highway system more reliable and longer lasting. These FRC materials could also be used for other structures such as columns, bridge decks, and highway barriers.

It should be noted again that this study has focused on the general effects of fiber reinforcement and the concrete mix used was different from those commonly used for highway pavements. However, similar toughening effect is expected for concrete with different cement/water/aggregate ratios when reinforced with fibers at the same volume fractions. Further studies are nonetheless needed to quantitatively assess the performance of highway concrete mixes reinforced with recycled fibers, field performance of such FRC, and the use of such fibers for asphalt reinforcement.

The carpet waste fibers used in this study were supplied by a waste recycling company and were used in the "as-is" state. However, highest FRC toughness can only be achieved when the reinforcement parameters such as fiber size, strength, and fiber/matrix bond properties are optimized [4,5]. Further studies to optimize the fiber length and bond behavior could improve the effectiveness of the carpet waste fiber reinforcement even further.

The experimental data in Table 1 illustrate that the carpet waste fiber reinforcement at 2% $V_f$ was at least as effective as that with 0.5% virgin polypropylene fibers in improving concrete toughness. The use of carpet waste fibers in FRC for highway construction is especially attractive. It could not only reduce or even eliminate the amount of carpet waste currently disposed in landfills, it at the same time would also provide better highways. A rough estimation indicates that 0.5 million tons of carpet waste would be consumed if 2% by volume of carpet waste fiber is added to the concrete for the construction of one thousand miles of highways.

Because of the rapid decrease in available landfill spaces, the disposal of carpet waste becomes increasingly difficult. Considering the vast amount of carpet waste disposed each year and a surcharge for landfilling is required in some areas, the carpet waste is expected to remain free of charge, even with possible free delivery. The disassemble process to convert the waste into fibers suitable for concrete reinforcement requires only simple shredding equipment and the overall operational cost is very low. It is estimated that the cost of such recycled fibers could be
ten times lower than that of virgin polypropylene fibers. Since the reinforcing fibers can be added to the concrete mix using existing concrete mixing equipment, only a slight increase in cost is expected when replacing concrete with FRC.

One concern with the use of concrete additives is their long term durability. Earlier studies have suggested that the major components in the carpet waste (polypropylene and nylon) are unattacked by the alkalinity of Portland cement [1,6], and are expected to be very durable in concrete. In fact, the excellent durability of carpet waste has contributed to the problem of disposing it in landfills, since it may take centuries for the waste to decompose.

**SUMMARY**

A large amount of carpet waste is disposed in landfills each year. This not only poses economical and environmental problems to the U.S. fiber/textile industry, it also represents a severe waste of recourses because the waste material can prove to be valuable for certain applications. This study focused on the use of carpet waste fibers in fiber reinforced concrete and demonstrated that such reinforcement can effectively improve the shatter resistance, toughness, and ductility of concrete. Such improvements in concrete performance is especially beneficial for highway construction as many signs of highway deterioration such as cracking, spalling, scaling, and pothole formation are associated with the brittle nature of ordinary concrete used in construction. The use of carpet waste fibers in highway construction could contribute to the healthy growth of the U.S. fiber/textile industry, a better environment, and more reliable, longer lasting highways.

Further studies of this work could include the enhancement of FRC performance by optimizing fiber size and surface treatment, evaluating other properties such as plastic and drying shrinkage, extension to include other types of textile waste, and field performance evaluation using such FRC in highway construction.

**ACKNOWLEDGMENT**

This work has been supported by the National Textile Center which is funded by the U.S. Department of Commerce. The fibers used were supplied through courtesy of Crown America, Inc. (carpet waste fiber) and FiberMesh, Inc. (polypropylene). Helpful discussions with Drs. M. B. Polk and S. Kumar are appreciated.

**REFERENCES**