

CONCRETE REINFORCEMENT WITH RECYCLED FIBERS

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ABSTRACT: Fiber reinforcement can effectively improve the toughness, shrinkage, and durability characteristics of concrete. The use of recycled fibers from industrial or postconsumer waste offers additional advantages of waste reduction and resources conservation. This paper reviews some of the work on concrete reinforcement using recycled fibers, including tire cords/wires, carpet fibers, feather fibers, steel shavings, wood fibers from paper waste, and high density polyethylene. This paper also provides a summary of the properties and applications of concrete reinforced with these fibers.

INTRODUCTION

Concrete is the most frequently used construction material in the world. However, it has low tensile strength, low ductility, and low energy absorption. An intrinsic cause of the poor tensile behavior of concrete is its low toughness and the presence of defects. Therefore improving concrete toughness and reducing the size and amount of defects in concrete would lead to better concrete performance. An effective way to improve the toughness of concrete is by adding a small fraction (usually 0.5–2% by volume) of short fibers to the concrete mix during mixing. In the fracture process of fiber reinforced concrete (FRC), fibers bridging the cracks in the matrix can provide resistance to crack propagation and crack opening before being pulled out or stressed to rupture. After extensive studies it is widely reported 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 (ACI 1982; Keer 1984; Wang et al. 1987; Bentur and Mindess 1990).

Another application of fiber reinforcement is for the reduction of the shrinkage and shrinkage cracking of concrete associated with hardening and curing. Plastic shrinkage cracks occur in fresh, unhardened concrete when the rate of evaporation at the concrete surface is greater than the rate of water migration to the surface. The volume of the fresh concrete decreases when there is a net loss of water, which is greater at the surface. This gradient in shrinkage forces cracks to appear on the surface. Because the strength and stiffness of fresh concrete is very low, only a small amount of fibers are needed to effectively reduce the plastic shrinkage. Low volume fractions of synthetic fibers, e.g., 0.1% of polypropylene fibers, are often used to reduce plastic shrinkage cracking in concrete.

Other benefits of FRC include improved fatigue strength, wear resistance, and durability. By using FRC instead of conventional concrete, section thickness can be reduced and cracking can be effectively controlled, resulting in lighter structures with a longer life expectancy. FRC is currently being used in many applications, including buildings, highway overlays, bridges, and airport runways (ACI 1982; Keer 1984; Bentur and Mindess 1990). In load bearing applications it is

generally used along with traditional steel reinforcement (ACI 1988). In building construction it has become a more common practice to use low-dosage synthetic fiber reinforcement for floor slabs.

Fibers for concrete reinforcement generally need to be durable in the cementitious environment, be easily dispersed in concrete mix, have good mechanical properties, and be of appropriate geometric configuration in order to be effective. Many fibers have been used for concrete reinforcement and some are widely available for commercial applications. They include steel, glass, natural cellulose, carbon, nylon, polypropylene, among others.

According to the U.S. Environmental Protection Agency (USEPA 1992), the municipal solid waste generated in the United States is ~200,000,000 tons/year, among them about 38% being paper products, 8% plastic, and 3% carpets and textiles. The practice of disposal requires constant creation of new landfill spaces, which is in contradiction to the nation's environmental goals, including ecosystem protection. Significant effort has been devoted to the reduction, reuse, and recycling of the waste materials. Typically, recycling technologies are divided into primary, secondary, tertiary, and quaternary approaches. Primary approaches involve recycling a product into its original form. Secondary recycling involves processing a used product into a new type of product that has a different level of physical and/or chemical properties. Tertiary recycling involves processes, such as pyrolysis and hydrolysis, which convert the waste into basic chemicals or fuels. Quaternary recycling refers to waste-to-energy conversion through incineration. All four approaches exist for textile, plastic, and paper recycling. Studies have indicated that many forms of fibers recovered from various waste streams are suitable for concrete reinforcement. The advantages of using such recycled fibers include generally lower cost to process than virgin fibers, and the elimination of the need for waste disposal in landfills. This paper reviews some of the work on concrete reinforcement using recycled fibers, including tire cords/wires, carpet fibers, feather fibers, steel shavings, wood fibers from paper waste, and high density polyethylene (HDPE). This paper also provides a summary of the properties and applications of concrete reinforced with these fibers.

RECYCLED FIBERS FROM CARPET WASTE

The carpet waste generated each year and accumulated in landfills represents an abundance of useful resources, as this waste may be converted into various useful products (Gardner 1995; Wang 1998). The amount of carpet waste, including production waste and postconsumer carpet, is estimated at over 2,000,000 tons/year. Because of the high cost of developing and managing landfills, waste disposal in landfills has become increasingly difficult.

A carpet typically consists of two layers of backing (usually fabrics from polypropylene tape yarns), joined by CaCO₃-filled styrene-butadiene latex rubber (SBR), and face fibers (the majority being nylon 6 and nylon 66 textured yarns) tufted into

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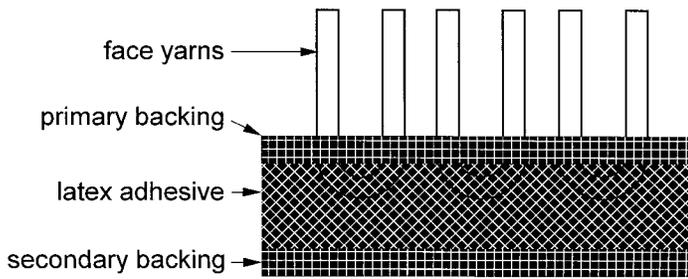


FIG. 1. Illustration of Tufted Carpet Structure

the primary backing, as illustrated in Fig. 1. The SBR adhesive is a thermoset material, which cannot be remelted or reshaped. Some waste is generated before the application of SBR. Such waste is termed “soft waste,” and most is reused as filling material or nonwoven mats. The waste containing the SBR (termed “hard waste”) has not been found to have significant uses and forms the major part of the waste going into the landfills. The fibers in most carpet waste are nylon face fibers and polypropylene tape yarns, both proven durable and effective in FRC. Therefore, it is logical to expect beneficial effects from recycled carpet waste fibers in concrete.

Laboratory Studies on Carpet Waste Fibers in Concrete

Wang et al. (1994) conducted a laboratory study on concrete reinforcement with carpet waste fibers. The concrete mix weight ratios were: Type I portland cement (1.0), river sand (0.85), crushed granite (0.61), water (0.35), and a small amount of superplasticizer. The recycled carpet waste fibers used were disassembled from hard carpet waste (typical length of 12–25 mm). Fiber volume fractions for the waste fibers were 1 and 2%. Only the actual fiber portion was included for calculating fiber volume fractions for the waste FRC.

FiberMesh (FM), a virgin polypropylene fiber (19-mm long), at 0.5 and 1% by volume fractions, was also included for comparison.

A four-point flexural test and cylinder compressive test were conducted on a hydraulic testing machine. In the compressive test, the plain concrete specimens failed in a brittle manner and shattered into pieces. In contrast, after reaching the peak load, all the FRC samples still remained as an integral piece, with fibers holding the concrete matrices tightly together. In the flexural test, it was observed that 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 pseudoductile behavior, and fibers bridging the beam crack could be seen. Because of the fiber-bridging mechanism, the energy absorption during flexural failure was significantly higher than that for plain concrete.

In commercial applications, low dosage reinforcement with synthetic fibers, mostly polypropylene at about 0.1% by volume, is widely used for controlling shrinkage cracking. For structural applications, however, a higher dosage (1–2% by volume) may be desirable. To evaluate the effect of fiber dosage rate on FRC properties, an intensive testing program was carried out on the flexural and compressive properties of concrete containing 0.89–17.85 kg/m³ of carpet fibers (Wang 1997). Since the carpet waste contains components other than fibers and since nylon has a higher density than polypropylene, the estimated fiber volume fraction for the recycled fiber is lower than that with virgin polypropylene, even at the same dosage rate based on fiber mass. The concrete mix used was in the following proportions: cement (1.00), water (0.44), sand (1.71), crushed rock (2.63), and an appropriate amount of fiber. No chemical admixtures were added. The test results are summarized in Table 1.

Good workability (180–230-mm slump) was reported for mixes with up to 1.8 kg/m³ of waste fibers. The slump decreases to 70 mm for 5.95 kg/m³, 51 mm for 8.93 kg/m³, 48

TABLE 1. Test Results for Concrete Reinforced with Carpet Waste Fiber (Wang 1997)

Mix (1)	Dosage (kg/m ³) (2)	Approximately V _f (%) (3)	Slump (mm) (4)	Compressive Strength		Flexural Strength		Toughness		
				MPa (5)	COV ^b (6)	MPa (7)	COV ^b (8)	I ₅ (9)	I ₁₀ (10)	I ₂₀ (11)
1	— ^a	0.15	178	22.8	0.11	3.74	0.09	3.22	4.69	6.33
2	0.89	0.07	229	20.0	0.12	3.64	0.07	3.64	3.07	4.21
3	1.34	0.11	184	24.3	0.13	4.20	0.07	4.20	2.98	4.01
4	1.79	0.14	191	25.6	0.08	4.06	0.08	2.96	4.06	5.03
5	5.95	0.47	70	27.6	0.07	3.79	0.07	2.71	3.64	4.76
6	8.93	0.70	51	23.7	0.02	4.11	0.08	2.95	4.17	5.77
7	11.90	0.93	48	23.1	0.14	3.77	0.07	3.06	4.41	6.41
8	17.85	1.40	0	17.4	0.20	3.73	0.10	3.29	5.17	7.91

^aWith FM polypropylene at 0.89 kg/m³.

^bCOV = Coefficient of variation.

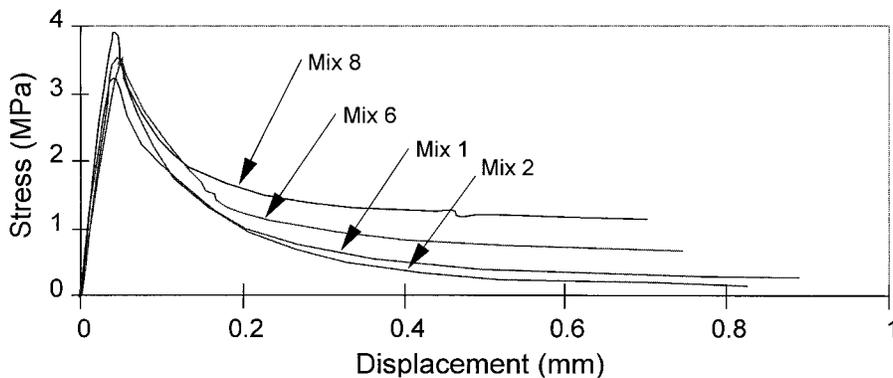


FIG. 2. Typical Flexural Test Curves of FRC

mm for 11.9 kg/m³, and to near zero for 17.85 kg/m³. The compressive strength for Mix 8 with 1.4% by volume waste fibers was lower due to the fiber addition. In all the tests, good shatter resistance was observed because of the fiber reinforcement, especially in those with relatively high fiber dosage rates (Mixes 5–8). Typical flexural test curves for selected mixes are shown in Fig. 2. The flexural strength, corresponding to the maximum flexural load in the test, was similar for all the mixes, suggesting that the addition of fibers to concrete had little effect upon the flexural strength of the concrete beams. The change in flexural toughness was quantified using the toughness index according to ASTM C 1018-92. The index is the area under the flexural test curve up to a specified displacement (δ) normalized by the area up to the matrix cracking. δ is equal to three times the cracking deflection (δ_c) and is used for I_5 , $\delta = 5.5 \delta_c$ for I_{10} , $\delta = 10.5 \delta_c$ for I_{20} , and $\delta = 15.5 \delta_c$ for I_{30} . The toughness index I_s values for the various mixes were insensitive to the fiber dosage rate. Toughness indices corresponding to larger beam deflections, I_{10} and I_{20} , generally increased with the dosage rate.

Field Study Using Carpet Waste Fibers in Construction

The laboratory study has indicated that the carpet waste fiber was very effective in improving the toughness and shrinkage properties of concrete. Shaw Industries, Inc., in 1994, completed an 11,000 m² R&D Center in Dalton, Ga., which used concrete reinforced with carpet waste fibers in the construction project (Wang 1995). About 20 tons of carpet production waste was consumed in the project, which would otherwise have been sent to a landfill. The concrete mix followed a typical design for concrete with a 28 MPa (4,000 psi) compressive strength, consisting of cement, sand, and rock. The water–cement ratio was 0.5 and the cement content was about 260 kg/m³. Superplasticizer was added to maintain the desired workability. The amount of waste fiber included was 5.95 kg/m³. Mixing was done by adding fibers to the mixing truck directly, after which the fibers were found to be uniformly dispersed in the concrete without balling or clumping. Mixing, pouring, and finishing followed standard procedures, used conventional equipment, and went smoothly. The compressive and flexural strengths exceeded specifications, and reduced shrinkage cracking was observed. Such concrete containing waste fibers was used for floor slabs, driveways, and walls of the building. The project demonstrated the feasibility of using large amounts of carpet waste for concrete reinforcement in a full-scale construction project. Besides reducing the need for landfilling, the use of low-cost waste fiber for concrete reinforcement could lead to improved infrastructure with better durability and reliability.

Use of Polypropylene and Nylon Fibers in Concrete

Naaman et al. (1996) investigated the effect of polypropylene fibers from carpet waste on the flexural and compressive behavior of concrete and mortar. The fibers were obtained from shredded carpet backing. The fiber length ranged from near 0 (powder) to about 25 mm, and about 40% of the fibers were shorter than 5 mm. Five fiber volume fractions were used: 0.15, 1.0, 1.3, 2.6, and 3.9%. The matrices included concrete with coarse aggregates, mortar with regular river sand, and mortar with very fine silica sand. Type I portland cement was used with a water-to-cement ratio of 0.60–0.63.

The study revealed that the waste polypropylene fibers were more efficient in matrices with finer aggregates. There was a significant improvement in the flexural properties with a 2.6% by volume fiber reinforcement. No significant improvement in bending was observed for V_f below 1.3%, and a slight decrease

in performance was observed when V_f increased from 2.6 to 3.9%. The compressive stress-strain behavior of concrete was not improved by the polypropylene fibers.

One series of tests utilized 2.6% by volume of waste polypropylene fibers that had undergone a plasma treatment process. The composite exhibited lower flexural strength and toughness in comparison with that containing untreated fibers. This was possibly due to a reduction of frictional bond when the fiber surfaces were cleaned by the plasma treatment. This finding was different from that on polyethylene fibers in which plasma treatment was found to enhance the bonding properties (Wu and Li 1997).

Groom et al. (1993) investigated the potential of using nylon fibers to reduce plastic shrinkage cracking in concrete. The nylon fibers were from waste nylon yarns from the carpet tufting operation, cut into a 6.4-mm or a 19.1-mm length. In their laboratory studies, the properties of fresh concrete and the flexural, compressive, and splitting tensile strengths of hardened concrete were not significantly affected by the inclusion of nylon fibers at a 0.6 kg/m³ dosage rate (about 0.13% by volume). In the plastic shrinkage study, 0.91 × 2.4 m panels with a thickness of 44.5 mm were cast in the field and the total area (length × width) of shrinkage cracks was measured 24 h later. In comparison to the control panel without fibers, the panel containing 0.6 kg/m³ of 6.4 mm fibers had the same total plastic shrinkage area, the one with 0.9 kg/m³ of 6.4 mm fibers had an 89% reduction, the one with 0.6 kg/m³ of 19.1 mm fibers had a 94% reduction, and the one with 0.9 kg/m³ of 19.1 mm fibers showed no plastic shrinkage crack at the time of measurement.

RECYCLED FIBERS FROM USED TIRES

Wu et al. (1994, 1996a,b) studied the use of recycled fibers from used tires and carpet in concrete to examine their effect on the free shrinkage and restrained shrinkage cracking behavior of concrete. The free drying shrinkage test followed the standard test methods of ASTM C 596 and ASTM C 157. The restrained cracking behavior was investigated using ring specimens of 31.0-cm inner diameter, 35.6-cm outer diameter, and 15.2-cm height, cast around a steel ring with a 2.16-cm wall thickness (Grzybowski and Shah 1990).

A total of four types of recycled fibers plus two types of virgin fibers were used as the reinforcement in concrete, as summarized in Table 2. Three recycled fibers were obtained from disposed tires and one from carpet waste. The tire fibers included two types of recycled tire fabrics [RTF(1) and RTF(2)] composed of polymeric tire cords, recycled tire-rubber strips (RTR), which were the main component of tires, and recycled tire steel fibers (RTS), which were the radial steel reinforcement of tires. The fibers from recycled carpet waste (RC) contained backing fibers (usually polypropylene), latex adhesive particles, and small amounts of face fibers. In addition, hooked-end steel fibers (SF) and FM polypropylene fibers were also used as virgin fibers for comparison. These two types of fibers were widely used for concrete reinforcement in

TABLE 2. Fibers from Used Tires for Shrinkage Studies

FRC (1)	Reinforcing fiber type (2)	Shape (3)
FMRC	FiberMesh Virgin Polypropylene (FM)	Ribbon, 19-mm long, 50 × 200- μ m cross section
SFRC	Virgin steel (SF)	Circular, 30-mm long, 0.5-mm diameter
RTSC	Recycled tire steel (RTS)	Circular
RCC	Recycled carpet (RC)	Irregular
RTF(1)C	Recycled tire fabric (RTF(1))	Irregular, from Company 1
RTF(2)C	Recycled tire fabric (RTF(2))	Irregular, from Company 2
RTRC	Recycled tire rubber strip (RTR)	Flake

the construction industry to control plastic shrinkage cracking with typically low fiber volume fractions (<0.5%).

Ordinary concrete with river sand and crushed aggregate (maximum size of 9.6 mm, cement:sand:aggregate = 1:1.72:1.72) was used for form the matrix of the composites. The water-to-cement ratio was 0.45 and the compressive strength of this concrete was 50 MPa. Superplasticizer was dosed in fiber reinforced composites to improve workability; however no superplasticizer was used in plain concrete and that containing virgin or recycled steel fiber. Recycled fiber volume fractions in each composite were fixed at 2%, except that the tire steel fiber and virgin fibers (SF and FM) were used at a 1% by volume fraction.

The free shrinkage of each composite was measured at different ages of exposure to the controlled environmental condition, and the results are shown in Fig. 3. The measured free shrinkage of concrete and FRC ranged from 700 to 1,200 microstrains, agreeing well with other reported data (Mindess and Young 1981). The free shrinkage of steel fiber reinforced con-

crete (SFRC) was about 7% lower than that of concrete, and recycled steel fiber composites (RTSC) showed about the same free shrinkage as concrete. On the other hand, the free shrinkage of FiberMesh reinforced concrete (FMRC) and the recycled fiber composites, except RTSC, was 23–57% higher than that of concrete. This adverse phenomenon might be attributed to the higher porosity in the composites compared to the plain concrete due to the addition of large amounts of synthetic fibers.

The restrained shrinkage cracking behavior, as measured by the total crack width of each ring specimen with respect to time, is shown in Fig. 4. The crack widths were significantly reduced in the fiber composites including all recycled fibers except recycled tire rubber composites (RTRC). The crack width of RTRC was much smaller than that of concrete before 12 days, but the crack width rapidly increased after 11 days and then became as wide as that of concrete. This sharp-opening phenomenon was found in other recycled fiber composites and might be due to the high Poisson's ratio of the tire rubber.

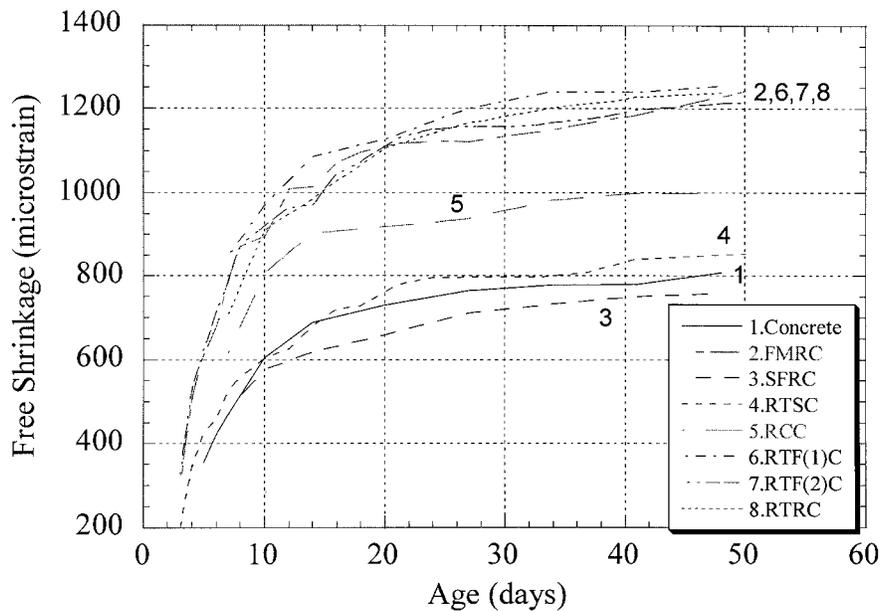


FIG. 3. Free Shrinkage at Different Ages for Concrete with Different Reinforcements (See Table 2 for Fiber Description)

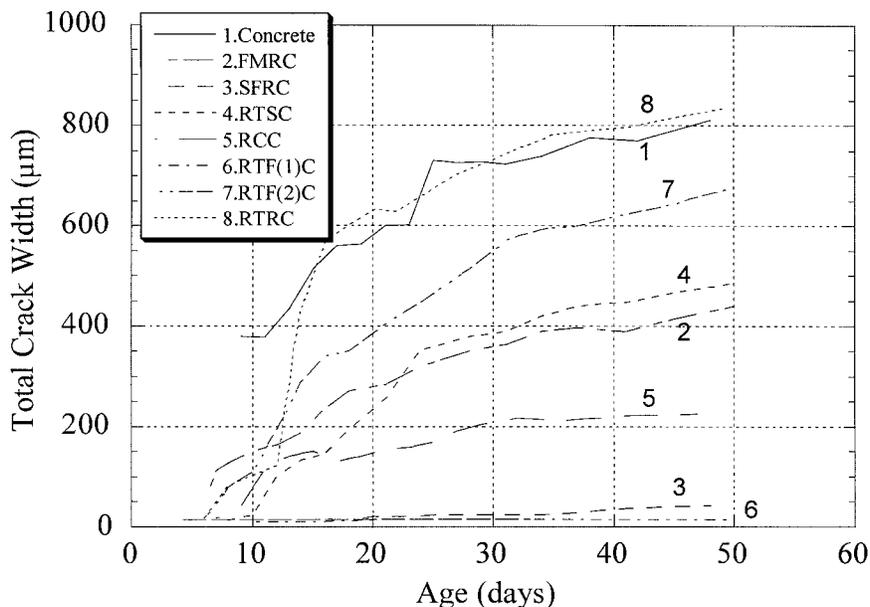


FIG. 4. Total Crack Width versus Ages in Restrained Shrinkage Test (See Table 2 for Fiber Description)

In the tire fabric composites, the crack width varied with the types of tire fabric used. RTF(1)C was comparable to the SFRC, even though the free shrinkage was much higher than that of SFRC (70% higher). The second type of tire fabric reinforced concrete, RTF(2)C, showed a much larger crack width than that of RTF(1)C and other recycled fiber reinforced composites. The difference between the two tire fabrics resulted from the different retrieving processes used in collecting these fibers. Therefore, fiber types, and particularly fiber geometry (e.g., fiber length), were apparently different in RTF(1)C and RTF(2)C. No attempt was made to quantify these differences.

The RTSC exhibited a very large crack width, 16.5 times higher than that of virgin steel fiber composites. It was noted that the majority of the recycled steel fibers was very short (<6 mm), probably too short to provide adequate bridging for restraining the crack opening. Nevertheless, the total crack width of RTSC was still comparable to that of virgin FMRC.

In the recycled carpet fiber composites, the crack width and spacing were evenly distributed. The crack widths were much larger than that of SFRC and RTF(1)C, but comparable to that of RTSC, and about one half of that for virgin FMRC. When the fiber volume fraction was considered, recycled carpet composites (RCC) ($V_f = 2\%$) performed similarly to FMRC ($V_f = 1\%$), since both fiber systems were mainly composed of polypropylene.

FIBERS FROM RECYCLED PAPER PRODUCTS

North America consumes about 13,000,000 tons of newsprint annually (Cunningham 1992). Reuse of old newsprint in the papermaking process requires the removal of contaminants introduced by the printing process, consumer, and collection process. This is particularly problematic for magazine wastepaper in recycling back into paper due to their high level of impurities. The fibers used in magazines are mainly chemical (kraft) pulp. Soroushian et al. (1992, 1995) proposed the use of magazine wastepaper as reinforcing fibers in thin-sheet cement products.

The recycled fibers used were derived from recycling of wastepaper (magazine) by dry mechanical processing. Two types of recycled fibers were used in their study; one was produced from 100% magazine paper, the other was made of mixed paper with 90% magazine and 10% newsprint (Soroushian et al. 1995). A slurry-dewatering method was employed in their study to produce a thin cement sheet. The influential variables in the slurry-dewatering process were first identified in an experimental study based on fractional factorial design. Among factors investigated, fiber mass fraction, level of substitution of virgin fibers with recycled ones, and fiber refinement conditions were found to have significant effects on the flexural performance of composites. These most influential variables were then optimized based on response surface analysis techniques. Optimization was based on flexural strength, initial stiffness, toughness of the composites, and the cost of the raw materials. They discovered that optimal composites can be obtained using 8% total fiber mass fraction, 50% substitution level of virgin with recycled fibers, and refinement (beating) of fibers to a Canadian Standard Freeness of 540. Compared to virgin cellulose fiber cement, the optimized recycled composites possessed similar flexural strength (1.6% less), somewhat lower toughness (15% less), but higher initial flexural stiffness (15% more). Recycled composites also showed reduced moisture movement (35% less), lower water absorption and moisture content (20% less), and higher density (8% more). The authors attributed these differences to the fine content of recycled fibers that played more of a filling role than a reinforcing role.

The long-term durability of wastepaper fiber-cement com-

posites were also studied by Soroushian et al. (1994). The thin cement composite boards, produced by the slurry-dewatering process, were subjected to repeated cycles of wetting, drying, and carbonation. Carbonation was considered a key element in the natural aging of cellulose fiber cement composites. Dissolution of calcium hydroxide in pore water, and its precipitation within cellulose fiber cores and at the interface zones, would be accompanied with carbonation, which turns calcium hydroxide into calcium carbonate and pronounces the weathering effects (Soroushian et al. 1994). Aging led to a minor increase in flexural strength by 5%, a major drop in flexural toughness by 30%, and a significant increase in flexural stiffness by 35%. The authors further discovered that the dominant mode of failure of the unaged composites was fiber pullout, whereas fiber rupture was the dominant mode for the aged composites. They attributed such differences to the presence of a dense fiber/matrix interface of the aged composites, resulting from filling with some hydration and carbonation products. This adverse effect of aging could be reduced by reducing the calcium hydroxide content and improving the water-tightness and the structure of interface zones (Soroushian et al. 1994).

In addition to wastepaper, wood waste and sawdust can be used in concrete as a lightweight aggregate capable of enhancing the weight-to-strength ratio, insulation properties, and toughness characteristics of concrete materials (Soroushian et al. 1992).

OTHER RECYCLED FIBERS

Other fibrous materials derived from various waste streams have also been studied for concrete reinforcement. Keyvani and Saeki (1997) investigated the use of steel shavings as a substitute for steel fibers in concrete. Steel shavings or chips are waste materials from metal machining, generally having a rough surface, toothed edges, and twisted sections. Fibers could be obtained by cutting the shavings into proper lengths. The authors found that the shavings were stronger than the original steel, with a typical tensile strength of 1,300 MPa, whereas that of the original steel was 700 MPa. The steel shaving fibers used had the following dimensions: 40–50 mm in length and 0.8–1.0 mm in equivalent diameter. Several fiber dosage rates were used from 25 to 150 kg/m³ (about 0.3–1.9% by volume). Their experimental results showed that the strength and toughness of concrete increased with the steel shaving fiber dosage rate. At the 150 kg/m³ rate, the reinforcement resulted in a 94% increase in flexural strength, 113% increase in tensile strength, 62% increase in splitting tensile strength, 80% increase in shear strength, and 800% increase in the flexural toughness index, compared to those of unreinforced concrete.

Auchey and Dutta (1996) conducted a study on the use of recycled HDPE fibers in concrete under extreme freeze-thaw conditions. HDPE is a plastic material often used for making containers for food and household chemicals. The fibers used in the study were cut from milk containers with a typical dimension of 19–38-mm long, 1.6-mm wide, and 1-mm thick, and their tensile strength was ~34 MPa. A 28 MPa compressive strength concrete mix was used and the fibers added were at 0.1, 0.2, and 0.4% by volume. At 28 days after casting, the cylinder specimens were subjected to the freeze-thaw cycles of repeated 1-h cooling at -20°C followed by a 1-h thawing at 20°C. The dynamic modulus of elasticity of the specimens was monitored to indicate the internal damage. The authors found that it was feasible to use recycled HDPE fibers as a secondary reinforcement for temperature and shrinkage influences in concrete structures subjected to extreme freeze-thaw conditions. The recycled HDPE fiber reinforced specimens provided an equal or higher resistance to freeze-thaw than the

control specimens and specimens containing commercial virgin polypropylene fibers at the same volume fractions.

Hamoush and El-Hawary (1994) studied the use of chicken feathers from poultry processing as fibers in concrete. They conducted flexural, splitting, and compressive tests on a portland cement concrete mix with a water-to-cement ratio of 0.6 and fiber volume fractions of 1, 2, and 3%. Low workability of fresh concrete was observed so a progressively larger amount of superplasticizer had to be added with the increase of V_f . A moderate increase in the flexural strength was observed for the 1% V_f reinforcement at 14 and 28 days, and a decrease in the strength for the 2 and 3% reinforcements. In the compressive and splitting tensile tests, the strengths decreased sharply as the fiber dosage rate increased. The authors attributed the adverse effect to the severe decay of the feather fibers in concrete.

CONCLUSION

Fiber reinforcement using different types of virgin fibers has been extensively studied, and often found to be effective in improving the toughness, shrinkage, and durability characteristics of concrete. The use of recycled fibers from industrial or postconsumer waste could offer additional advantages of waste reduction and resources conservation. In the United States alone, the municipal solid waste generated is about 200,000,000 tons/year, among them about 38% being paper products, 8% plastics, and 3% carpets and textiles. As demonstrated in many studies, some of the recycled fibrous materials can offer effective reinforcement for concrete. This paper provides a review on some of the work on concrete reinforcement with recycled fibers, including tire cords/wires, carpet fibers, feather fibers, steel shavings, wood fibers from paper waste, and HDPE.

Because different mixes, testing conditions, and fiber configurations were used by different researchers, a direct comparison of a given property value was not possible. However, it has generally been observed that the recovered fibers could provide similar reinforcement as virgin materials, although a higher dosage rate may be required to match the performance. This was demonstrated in studies on recycled synthetic fibers from various sources including carpet, tires, and plastic containers in comparison with commercially available virgin synthetic fibers, and in studies on recycled steel fibers from tires and shavings compared to commercial steel fibers.

Fibers for concrete reinforcement generally need to be durable in the cementitious environment, be easily dispersed in concrete mix, have good mechanical properties, and be of appropriate geometric configuration in order to be effective. There is a need for further studies to process the fibers for an optimal reinforcement effect. The durability of some of the recycled fibers can be learned from the behavior of the corresponding virgin materials, but for some others, studies must be conducted to assess and improve their durability in portland cement concrete. All but a few studies on recycled FRC reported were laboratory investigations. Despite its benefits, a significant effort is needed to make recycled FRC widely acceptable and used in commercial constructions.

It is nonetheless very encouraging that the use of low-cost waste fiber for concrete reinforcement could lead to improved infrastructure with better durability and reliability. Potential applications could include buildings, pavements, columns, bridge decks and barriers, and for airport construction such as runways and taxiways.

APPENDIX. REFERENCES

- American Concrete Institute (ACI). (1982). "State-of-the-art report on fiber reinforced concrete." *Committee 544 Rep., ACI 544.1R-82 (Reapproved 1986)*, Detroit.
- American Concrete Institute (ACI). (1988). "Design consideration for steel fiber reinforced concrete." *Committee 544 Rep., ACI 544.4R-88*, Detroit.
- Auchey, F. L., and Dutta, P. K. (1996). "Use of recycled high density polyethylene fibers as secondary reinforcement in concrete subjected to severe environment." *Proc., Int. Offshore Polar Engrs. Conf.*, Int. Soc. of Offshore and Polar Engineers (ISOPE), Golden, Colo., 4, 287–291.
- Bentur, A., and Mindess, S. (1990). *Fiber reinforced cementitious composites*, Elsevier, London.
- Cunningham, H. W. (1992). "Old newspapers: Opportunities and challenges in using a fiber resource." *Proc., Mat. Res. Symp.*, R. M. Rowell, et al., eds., Vol. 266, 243–248.
- Gardner, H. C. (1995). "Carpet recycling technology." *Int. Fiber J.*, 10(4), 36–49.
- Groom, J. L., Holmquist, D. V., and Yarbrough, K. Y. (1993). "Use of waste nylon fibers in portland cement concrete to reduce plastic shrinkage cracking." *Proc., Recovery and Effective Reuse of Discarded Materials and By-Products for Construction of Highway Facilities*, Denver, 179–183.
- Grzybowski, M., and Shah, S. P. (1990). "Shrinkage cracking of fiber reinforced concrete." *ACI Mat. J.*, 87(2), 138–148.
- Hamoush, S. A., and El-Hawary, M. M. (1994). "Feather fiber reinforced concrete." *Concrete Int.: Design and Construction*, 16(6), 33–35.
- Keer, J. G. (1984). "Fiber reinforced concrete." *New reinforced concretes: Concrete technology and design*, R. N. Swamy, ed., Surrey University Press, 2, 2–105.
- Keyvani, S. A., and Saeki, N. (1997). "Behavior of fiber concrete composites using recycled steel shavings." *J. Solid Waste Technol. and Mgmt.*, 24(1), 1–8.
- Mindess, S., and Young, J. F. (1981). *Concrete*, Prentice-Hall, Englewood Cliffs, N.J.
- Naaman, A. E., Garcia, S., Korkmaz, M., and Li, V. C. (1996). "Investigation of the use of carpet waste PP fibers in concrete." *Proc., Mat. Engrg. Conf.*, K. Chong, ed., ASCE, New York, 782–791.
- Soroushian, P., Arola, R., and Shah, Z. (1992). "Recycling of wood and paper in cementitious materials." *Proc., Mat. Res. Symp.*, R. M. Rowell, et al., eds., Vol. 266, 165–175.
- Soroushian, P., Won, J. P., and Hsu, J. W. (1994). "Control of aging processes in wastepaper fiber reinforced cement." *Proc., 3rd Mat. Engrg. Conf.*, K. Basham, ed., ASCE, New York, 539–544.
- Soroushian, P., Shah, Z., and Won, J. P. (1995). "Optimization of wastepaper fiber-cement composites." *ACI Mat. J.*, 92(1), 82–92.
- U.S. Environmental Protection Agency (USEPA). (1992). "Characterization of municipal solid waste in the United States." *EPA/530-S-92-019 Rep.*, Washington, D.C.
- Wang, Y., Backer, S., and Li, V. C. (1987). "An experimental study of synthetic fiber reinforced cementitious composites." *J. Mat. Sci.*, 22, 4281–4291.
- Wang, Y., Zureick, A. H., Cho, B. S., and Scott, D. E. (1994). "Properties of fiber reinforced concrete using recycled fibers from carpet industrial waste." *J. Mat. Sci.*, 29(16), 4191–4199.
- Wang, Y. (1995). "Reuse of carpet industrial waste for concrete reinforcement." *Disposal and recycling of organic and polymeric construction materials*, Y. Ohama, ed., E & FN Spon, London, 297–305.
- Wang, Y. (1997). "Properties of concrete reinforced with recycled carpet waste fibers." *Brittle matrix composites 5*, A. M. Brandt, V. C. Li, and I. H. Marshall, eds., Woodhead Publishing, Cambridge, U.K., 179–186.
- Wang, Y. (1998). "An overview of activities on recycling of fibrous textile and carpet waste at the Georgia Institute of Technology." *Proc., 2nd Int. Textile Envir. Conf. (Ecotextile '98)*, Bolton, U.K., 134–142.
- Wu, H. C., Lim, Y. M., and Li, V. C. (1994). "Shrinkage behavior of cementitious composites with recycled fibers." *Proc., 2nd Annu. Great Lakes Geotech./Geoenvir. Conf. on Waste Mat. and Their Geotech./Geoenvir. Applications*.
- Wu, H. C., Lim, Y. M., Li, V. C., and Foremsky, D. J. (1996a). "Utilization of recycled fibers in concrete." *Proc., Mat. Engrg. Conf.*, K. Chong, ed., ASCE, New York, 799–808.
- Wu, H. C., Lim, Y. M., and Li, V. C. (1996b). "Application of recycled tire cord in concrete for shrinkage crack control." *J. Mat. Sci. Lett.*, 15, 1828–1831.
- Wu, H. C., and Li, V. C. (1997). "Basic interfacial characteristic of polyethylene fiber/cement composites and its modification by plasma." *Brittle matrix composites 5*, A. M. Brandt, V. C. Li, and I. H. Marshall, eds., Woodhead Publishing, Cambridge, U.K., 14–23.