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Properties of fibre reinforced concrete using recycled fibres from carpet industrial waste

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A study was carried out to evaluate the use of recycled fibres from carpet industrial waste for reinforcement of concrete at 1 and 2 vol % fractions. Compressive, flexural, splitting tensile and shrinkage tests were performed. Significant increases in shatter resistance, energy absorption and ductility were observed. This paper reports on the experimental programme and compares the effectiveness of such recycled fibres with that of virgin polypropylene fibres specially made for fibre reinforced concrete (FRC). The paper also discusses the benefits of using such FRC for construction applications and possible ways to further enhance the performance of such FRC.

1. Introduction

Concrete is the most frequently used human-made material in the world. It is durable, inexpensive, readily moulded 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 bars (rebars) in structural applications. Such applications under abusive environmental conditions often results in corrosion of the steel rebars, subsequently contributing to the decay of reinforced concrete structures.

An intrinsic cause of the poor tensile behaviour of concrete is its low toughness and the presence of defects. Therefore, improving concrete toughness and reducing the size and number of defects in concrete would lead to better performance. An effective way to improve the toughness of concrete is by adding a small fraction (usually below 2 vol %) of short fibres to the concrete during mixing. In the fracture process of fibre reinforced concrete (FRC), fibres 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 schematically in Fig. 1. After extensive studies in the last three decades, it is now beyond doubt that such fibre reinforcement can significantly improve the tensile properties of concrete. Orders of magnitude increase in toughness (energy absorption) over plain concrete is commonly observed. Improved fatigue strength and reduced drying shrinkage are also often observed. Fibre 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 [4]. By using FRC instead of conventional concrete, section thickness can be reduced and cracking can be effectively controlled, resulting in lighter structures with longer life expectancies.

This paper reports on an experimental programme to evaluate the effectiveness of using recycled fibres from carpet waste for concrete reinforcement. The tests performed include compression, flexure, splitting tensile and shrinkage. Descriptions of the raw materials used and experimental procedures will be provided. Test results will be presented and discussed. Possible ways to further improve the performance of such FRC will also be discussed based on the results of a direct fibre pull-out test.

2. Research significance

A significant amount of fibrous waste from the textile industry and post-consumer product is disposed worldwide. This is not only a cause for environmental concern, but also represents a waste of useful resources. As is demonstrated in this study, some of the

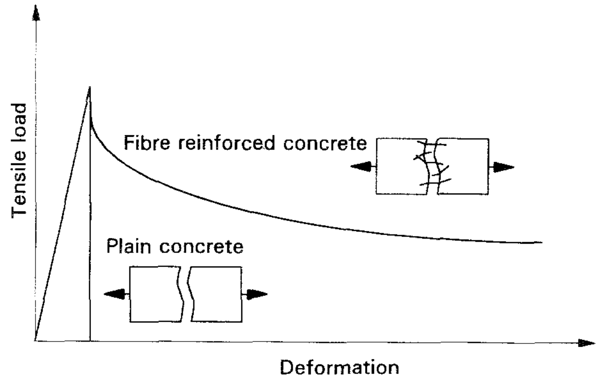


Figure 1 Schematic illustration of fibre bridging action in FRC.

waste materials can provide effective enhancement of concrete properties, leading to better and more reliable concrete structures at very low cost. It is expected that the paper will stimulate further full-scale studies on waste fibre reinforced concrete and promote the use of such a material in construction.

3. The carpet industrial waste

Fibres commonly used in FRC include steel, alkali-resistant glass and various synthetic fibres, most notably polypropylene. This work has focused on the recycled fibres from carpet industrial waste. The findings of this work could also be applicable to other textile industrial waste and waste from post-consumer goods.

The US carpet industry produces about 1 billion m^2 of carpet and consumes about 1 million tons of synthetic fibres. About 70% of the carpet produced is for replacement of used carpet, which translates into ca. 1.7 million tons of used carpet for disposal. In Dalton, GA, alone, where many carpet manufacturers are located, about 40 000 tons of carpet waste (including lint) has to be disposed of each year. Finding available landfill space has become increasingly difficult, resulting in serious environmental concerns that may have adverse effects on the carpet industry.

A carpet typically consists of two layers of backing (usually polypropylene), joined by $CaCO_3$ filled styrene–butadiene latex rubber (SBR), and face fibres (the majority being nylon 6 and nylon 6.6) tufted into the primary backing, as illustrated in Fig. 2. The nylon face fibre is often in the form of a heavily crimped loose filament bundle known as a textured yarn. The polypropylene backing fibre is often made from the slit-film process in the form of a tape yarn. 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 6.6 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 recycled carpet waste fibres used in this study were from hard carpet waste, disassembled mechanically by the Crown America, Inc., Dalton, GA. After disassembling, surface yarns (nylon) and some backing fibres (polypropylene) were collected. This collection is referred to as "Type I waste fibre", which has a typical length range of 12–25 mm. The disassembled waste after removal of the Type I fibre is referred to as "Type II waste fibre", which contains backing fibres, SBR coated face yarns, loose face yarns and SBR particles. The Type II waste fibre was analysed using a set of five sieves with different mesh sizes and a vibrating table. The analysis indicated that the fibre length for Type II was ca. 3–25 mm and that about one-third by weight was fibre, the other two thirds being $CaCO_3$ filled SBR. Type II waste fibres are shown in Fig. 3.

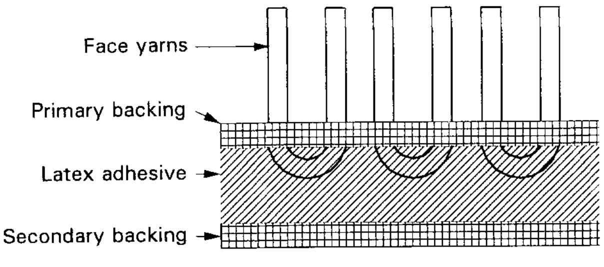


Figure 2 Illustration of tufted carpet structure.

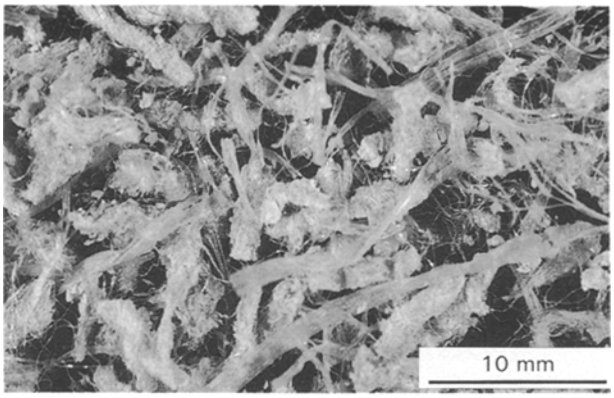


Figure 3 Photograph of Type II fibre from carpet waste.

4. Materials and mix proportions

4.1. Fibres and fibre volume fractions

Both Type I and Type II waste fibres were used in this study, and the fibre volume fractions for the waste fibres were 1 and 2%. Only the actual fibre portion was included for calculating fibre volume fractions for Type II waste fibre reinforced concrete.

FiberMesh® virgin polypropylene fibre at 0.5 and 1 vol % was also included in this study for comparison purposes. This fibre is one of the commercially available fibres specially targeted for use in FRC. The fibre length was 19 mm.

4.2. Matrix materials

Cement, Type I Portland cement; sand, a fine to medium river sand; aggregate, crushed granite with a maximum size of 10 mm; superplasticizer, a high-range water reducing admixture (ASTM C494 A, F or G).

4.3. Mix proportions

The weight proportions for specimens for mechanical property tests were 1.0 (cement)/0.35 (water)/0.85 (sand)/0.61 (aggregate); 2.5 wt % of superplasticizer relative to the water weight was also added to improve the workability. The proportions for the drying shrinkage specimens were 1.0 (cement)/0.6 (water)/2.0 (sand)/2.0 (aggregate); no superplasticizer admixture was added to this mix. The amount of water given above includes the moisture in the sand and the aggregate, which was determined by oven-drying of sand and aggregate samples.

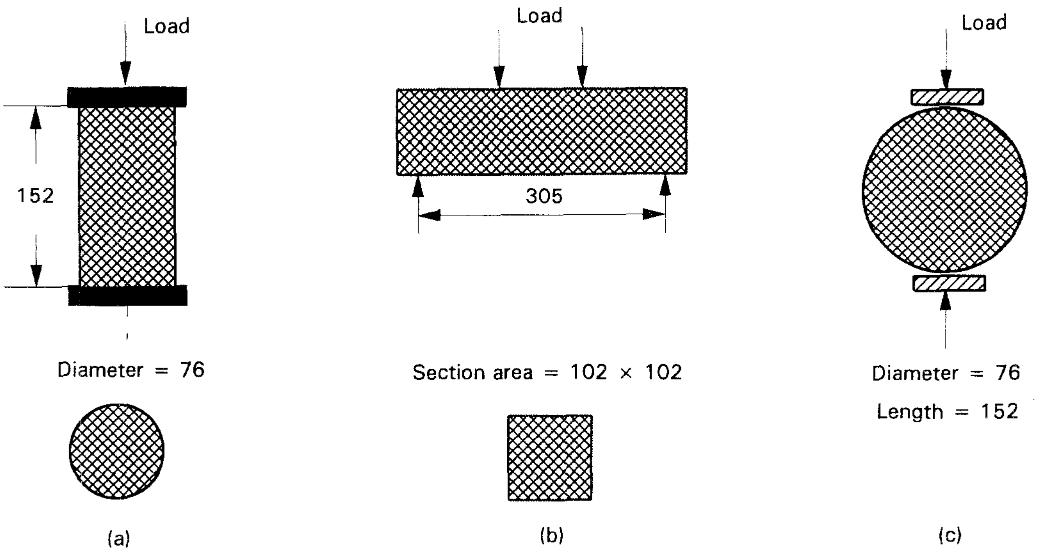


Figure 4 Test set-up for (a) compression test, (b) flexural test and (c) splitting tensile test (in mm).

5. Strength and flexural toughness

Measurements of FRC responses under different loading conditions were performed in compression, flexure and splitting tension. Beams ($102 \times 102 \times 356\ \text{mm}^3$) were tested for the flexural behaviour and cylinders (76 mm in diameter and 152 mm in height) were used in the one-day compressive, 28-day compressive and splitting tensile tests. Strength and flexural toughness values for different mixes were calculated.

5.1. Sample preparation

For each mix, six beams and at least 18 cylinders were prepared. A drum mixer was used for mixing. Superplasticizer was measured and added to the water before mixing. Aggregate, sand and cement were first dry mixed until a uniform consistency was obtained. The fibres were then hand-dispersed into the mixer and mixed until a uniform consistency was obtained before water was added for wet mixing. The mixing time was ca. 10 min for dry mixing and 10 min for wet mixing.

The freshly mixed concrete was filled into rigid Plexiglas moulds for the beam specimens, and into PVC plastic moulds for the cylinders. The moulds were coated with form-oil prior to filling for easy removal of the specimens. Specimens were consolidated externally on a vibrating table until all visible air bubbles had disappeared. Internal vibration or rodding was not used in accordance with ASTM C 1018 to avoid non-uniform fibre distribution. A steel spatula was used to finish the top surface after vibration. The specimens were then covered with a plastic sheet and placed in a mist curing room (ca. 100% relative humidity, 23 °C temperature).

The specimens were removed from the moulds after one day of curing and placed back in the curing room (except six cylinders for the one-day compressive test). The specimens were moved to the testing laboratory for drying one day before the 28-day tests. Actual dimensions (diameter and length for cylinders, and depth and width for beams) were measured at three locations and the average values were used in calculations.

5.2. Test configurations

Configurations for the four-point flexural test, the cylinder compressive test and the cylinder splitting tensile test are illustrated schematically in Fig. 4. All the tests were performed on a Tinus-Olsen hydraulic testing machine. 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 $0.25\ \text{mm}\,\text{min}^{-1}$ for all the tests. The age of specimens at testing was 28 days, except for the one-day compressive test.

Compression cylinders of 76 mm in diameter and 152 mm in height were tested according to ASTM C 39. The specimens were first capped with a sulphur-based capping compound to allow uniform loading. Specimen ages at testing were 1 and 28 days. The compressive strength was calculated from the maximum load divided by the cylinder cross-sectional area.

The flexural test was performed according to ASTM C 78 and C 1018 at a span length of 305 mm. The steel loading fixture was made following ASTM C 78. Beams were turned 90° from the casting position to ensure even loading. Beam deformation was measured at the centre point with the LVDT. The maximum tensile stress in the beam at peak load was taken as the flexural strength, given by

$$\sigma = \frac{PL}{BH^2}$$

where P is the peak load, L is the beam span length (305 mm), B is the beam width (102 mm) and H is the beam height (102 mm). Calculation of toughness indices will be described in the next section.

The splitting tensile test of cylinder was conducted in general accordance with ASTM C 496. The load was applied by the machine platens through two plywood strips (25 mm wide, 3.2 mm thick). The strips allowed even load distribution by conforming to small irregularities on the specimen surface. The splitting tensile strength is given by

$$\sigma = \frac{2P}{\pi DL}$$

where P is the maximum load, D is the cylinder diameter (76 mm), and L is the cylinder length (152 mm).

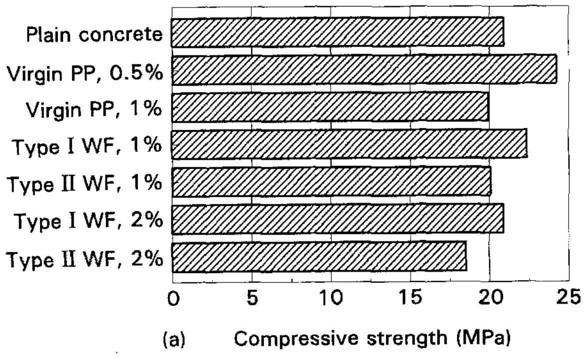
For each test configuration, six or seven specimens were tested for each mix.

5.3. Test results

The strengths from compressive, flexural and splitting tensile tests of various mixes are summarized in Table I.

Fig. 5 compares the compressive strengths of various FRCs. In the one-day compressive test similar strength values were observed for plain concrete and various FRCs. The 28-day compressive strengths of FRCs with 2 vol % carpet waste fibres were lower than that of plain concrete, indicating that the fibres might have caused a strength reduction, or they might have delayed the development of compressive strength with age.

The 28-day compressive strengths for all the mixes tested were ca. 40 MPa or higher, which were in the general range where normal strength concrete and high strength concrete overlap. The plain concrete specimens failed in a brittle manner and shattered into



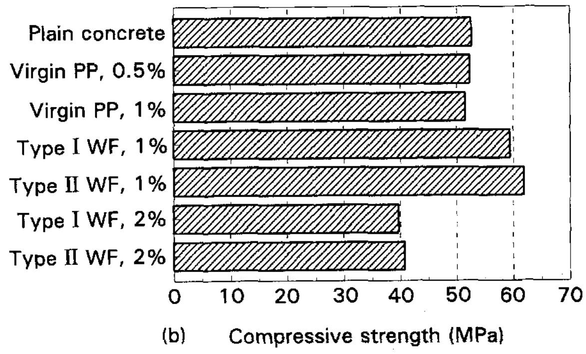


Figure 5 Compressive strengths: (a) 1-day test and (b) 28-day test.

TABLE I Results of compressive, splitting tensile and flexural strengths and flexural toughness (all tests at 28 days except 1-day compression)

Fibre in FRC mix	V_f (%)	Compressive strength 1 day MPa	(CV%)	28 days MPa	(CV%)	Splitting tensile strength MPa	(CV%)	Flexural strength MPa	(CV%)	Flexural toughness indices I_5 (ASTM C 1018-92)	I_{10}	I_{20}	TI ([6])
Concrete control	0	20.9	(4.9)	52.6	(3.1)	6.39	(6.5)	4.65	(4.0)	1.0	1.0	1.0	1.0
Fibre Mesh PP	0.5	24.2	(3.7)	52.2	(1.4)	7.25	(4.3)	4.58	(3.1)	2.6	4.3	6.9	4.7
Fibre Mesh PP	1.0	19.9	(5.4)	51.5	(5.7)	–		4.99	(9.8)	3.3	6.4	12.5	12.0
Type I waste fibre	1.0	22.4	(16.8)	59.4	(10.3)	–		5.24	(9.0)	1.8	2.9	4.4	1.9
Type II waste fibre	1.0	20.1	(2.2)	61.8	(5.9)	–		4.09	(10.9)	2.1	3.4	5.4	2.2
Type I waste fibre	2.0	20.9	(5.7)	39.7	(7.4)	6.99	(4.3)	4.69	(2.3)	3.3	5.3	7.5	6.0
Type II waste fibre	2.0	18.6	(7.6)	40.7	(7.4)	6.62	(4.7)	4.35	(4.3)	3.5	6.1	9.8	8.1

pieces as the load dropped instantly to zero. In contrast, all the FRC samples after reaching the peak load could still remain as an integral piece, with fibres holding the concrete matrices tightly together, and could still take up to 30% of the peak load. Some typical compressive test curves are shown in Fig. 6 and photographs of FRC samples after testing are given in Fig. 7. It appears that FRC with 2 vol % waste fibres were less brittle than that with 0.5 vol % polypropylene fibres.

The splitting tensile strengths for various mixes are compared in Fig. 8. This test provides a simple measure of the tensile strength of plain concrete and the cracking stress for FRC. There was no noticeable difference in strength among the samples tested. Again, all the FRC samples failed in a shatter-contained manner while the plain concrete specimens failed in a brittle manner.

Fig. 9 shows the flexural strengths from the four-point beam bending test. It can be seen that the flexural strengths of all mixes tested were essentially the same. Fig. 10 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 behaviour. A photograph of an FRC specimen containing virgin polypropylene fibres during the flexural test is shown in Fig. 11, in which fibres bridging the beam crack can be seen. Similar post-matrix crack behaviour was also observed for other FRCs. For the FRC samples tested, the load carrying capacity was as high as 40% of the flexural strength, even when the beam deflection had exceeded several times the cracking deflection with crack opening exceeding several millimetres in width. As seen from the flexural test curves, the ultimate deflection for the final failure of an FRC beam is very large, indicating the exceptional ductility of FRC material.

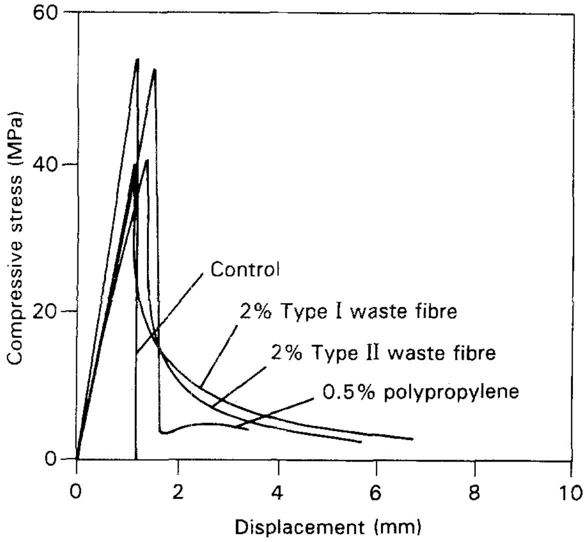


Figure 6 Some typical 28-day compressive test curves.

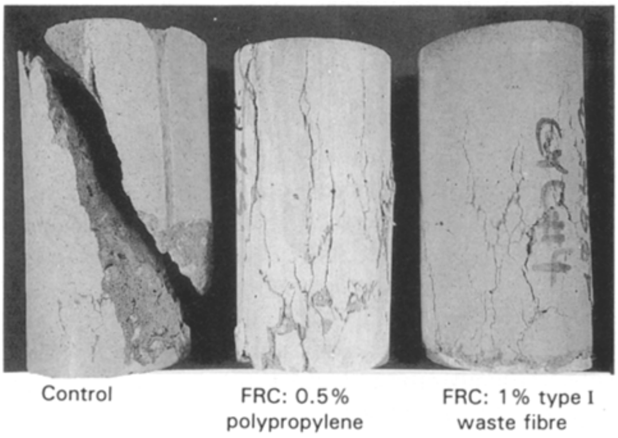


Figure 7 Photographs of compressive test cylinders after 28-day test.

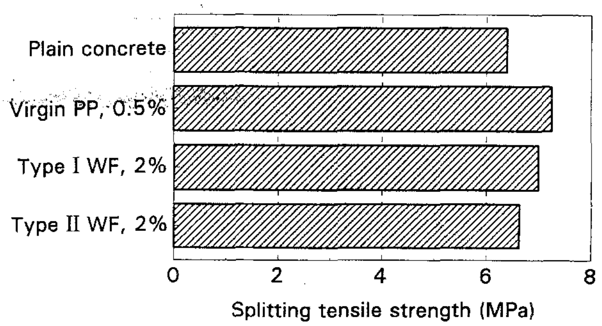


Figure 8 Splitting tensile strength.

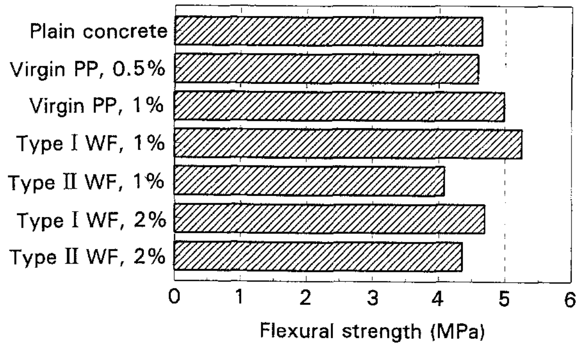


Figure 9 Flexural strength.

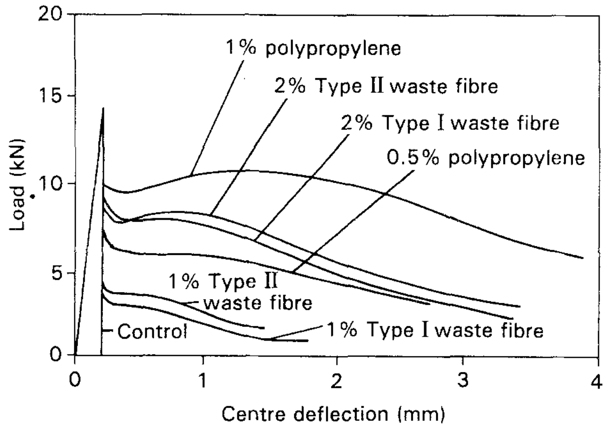


Figure 10 Typical flexural test curves.

Both the flexural and splitting tensile tests provide information about the tensile strength of plain concrete and the cracking strength of FRC. It is normally observed that the flexural strength, σ_{FL}, is higher than

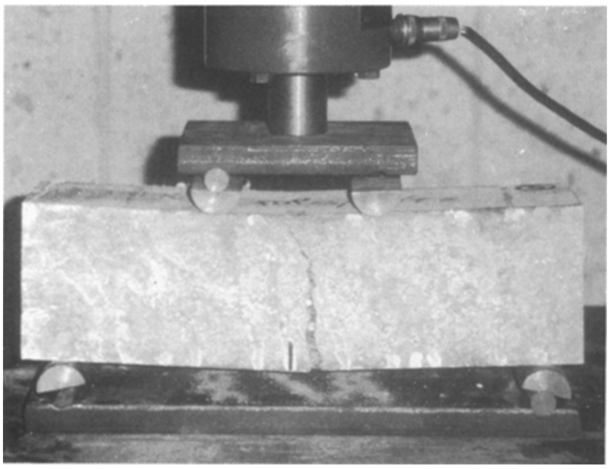


Figure 11 Photograph of an FRC beam (with polypropylene fibre) in flexural test after matrix cracking showing fibres bridging the crack.

the splitting tensile strength, σ_{ST}. In this study, however, σ_{ST} was observed to be higher than σ_{FL}. The most likely reason is that the cylinder size for the splitting tensile test used (76 mm diameter) was much smaller than the size normally used (152 mm diameter) (ASTM C 496). For small cylinders the load applied through a pair of loading strips (width 25 mm) can no longer be regarded as an edge load, and the actual loading mode may be compression dominated. The ratio between σ_{FL} and the square root of the compressive strength (σ_C), $\sigma_{FL}/\sqrt{\sigma_C}$, for the concrete control sample was $0.641\sqrt{\text{MPa}}$, which was very close to the empirical value of $0.623\sqrt{\text{MPa}}$ ($7.5\sqrt{\text{psi}}$) given in the ACI Building Code [5].

Because of the fibre 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 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 matrix cracking. δ equal to three times the cracking deflection (δ_c) is used for I_5, $\delta = 5.5\ \delta_c$ for I_{10} and $\delta = 10.5\ \delta_c$ for I_{20}. Wang and Backer [6] have compared different methods for quantifying FRC toughness and proposed a toughness index (TI) calculated from the area under the flexural test curve up to a point specified by the displacement-to-load ratio, or the secant compliance. The ending point for the area to be included in the index calculation is where the secant compliance has reached 20 times the initial compliance. They argued that the proposed TI could provide a more objective quantification of the toughness characteristics of FRC by consistently excluding the curve tail portion with near-zero load. The definitions of these toughness indices are illustrated in Fig. 12. The value of a TI indicates the energy absorption of FRC compared with a brittle material, such as concrete (TI = 1.0) for the deformation range specified. For example, an FRC with $I_{10} = 10$ absorbs ten times as much energy as a brittle material when the beam deflection is increased to 5.5 times the deflection at cracking.

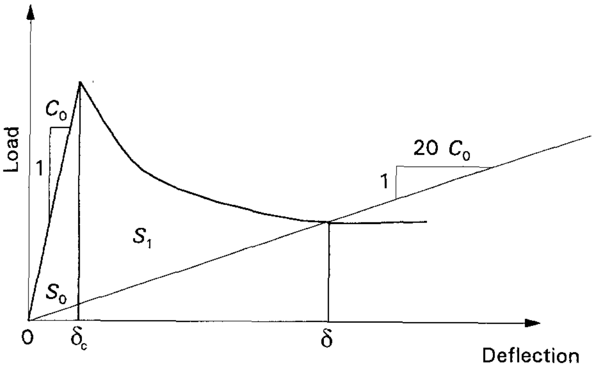


Figure 12 Definitions of toughness indices (TI). TI = $(S_0 + S_1)/S_0$, where S_1 terminates at deflection δ. δ equals to 3, 5.5 and 10.5 times δ_c for T_5, T_{10} and T_{20}, respectively, and δ is determined by the secant compliance as shown for TI by Wang and Backer [6].

Values for the beam samples tested are included in Table I. It can be seen that for the same type of fibre used, the FRC toughness increased with the fibre volume fraction. No noticeable difference in FRC strengths and toughnesses was observed between FRC with Type I waste fibre and that with Type II waste fibre at the same volume fraction. The highest toughness was found in FRC with 1 vol % FiberMesh® polypropylene. FRCs with 1 vol % Type I and Type II waste fibres exhibited the lowest toughness improvement, with low toughness index vlaues. FRCs with 2 vol % of the waste fibres showed a significant increase in toughness, with I_{20} and TI values consistently higher than those for FRC with 0.5 vol % polypropylene fibre, and much greater than 1.0, the TI for plain concrete.

6. Drying shrinkage

Concrete undergoes a volume change as it dries after casting. Deformation due to drying shrinkage, when restrained, is one of the major reasons of cracking in concrete. Positive effects of fibre reinforcement on controlling concrete drying shrinkage and shrinkage cracking has been reported [7–12].

ASTM C 157 recommends a prismatic specimen for measuring drying shrinkage. In this study four prism specimens of $50.8 \times 50.8 \times 635^3$ mm were prepared for each mix using rigid Plexiglas moulds. The mixes evaluated for shrinkage were: concrete control ($V_f = 0$), FRC with 0.5 vol % FiberMesh® polypropylene, FRC with 1 vol % FiberMesh® polypropylene, FRC with 2 vol % Type I waste fibre and FRC with 2 vol % Type II waste fibre. The mixing procedure for the shrinkage specimens was similar to that for beams and cylinders as described earlier. After consolidation by external vibration, the specimens were covered with a plastic sheet and allowed to cure for 24 h in the laboratory. They were then removed from the moulds and placed on a holding platform for the shrinkage monitoring in an air-conditioned chamber where a constant temperature of 19.5 ± 0.3 °C and a constant relative humidity of 50 ± 2% were maintained.

The shrinkage test set-up is shown in Fig. 13. Shrinkage data were taken with a dial gage (resolution = 2.5 μm, equivalent to a 4×10^{-6} axial strain)

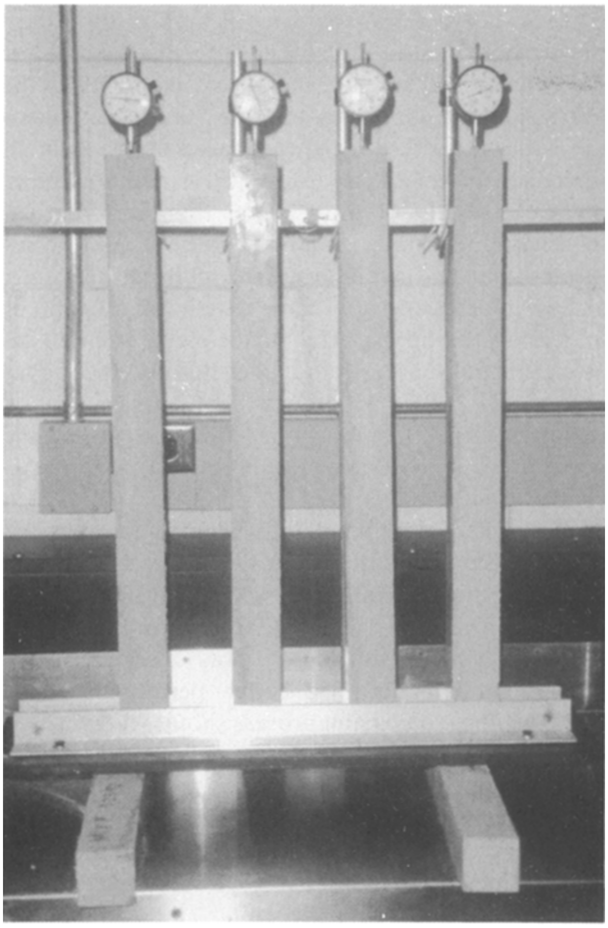


Figure 13 Drying shrinkage test set-up.

which measured the specimen length change. Readings were taken at equal intervals six times in the first day after demoulding, four times for the second and the third days, and twice thereafter, up to a total period of 21 days (500 h).

Fig. 14 presents the results of the shrinkage test in which each curve represents the average from four specimens. The readings from the four specimens in each group were very consistent. It can be seen from the results that the drying shrinkage of all the FRC samples was lower than that of plain concrete. FRC with 0.5 vol % FiberMesh® polypropylene, FRC with 2 vol % Type I waste fibre and FRC with 2 vol % Type II waste fibre all showed similar shrinkage. FRC with 1 vol % FiberMesh® polypropylene showed an even lower shrinkage. The reduction in drying shrinkage due to fibre reinforcement was generally in the range of 15–30% after 500 h of drying. The amount of shrinkage reduction observed in this study was similar to that for various fibre reinforcements reported by other researchers, including Zollo *et al.* [7] (polypropylene fibre, 14–25% reduction), Magnet and Azari [8] (steel fibre, 13–30% reduction) and Swamy and Stavrides [9] (glass, steel and polypropylene fibres, 10–20% reduction).

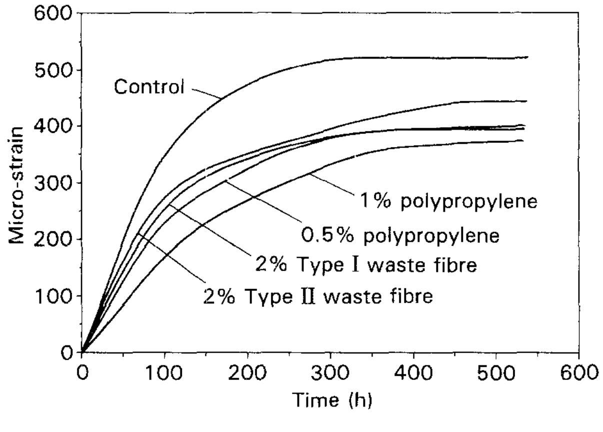


Figure 14 Drying shrinkage versus time.

7. Discussion

It has been demonstrated in this study that recycled fibres from carpet industrial waste can be used in fibre reinforced concrete to achieve improved toughness, shatter resistance and reduced drying shrinkage. The carpet waste fibre reinforcement at 2 vol % was found to be more effective than that with 0.5 vol % virgin polypropylene fibres. The disassemble process to convert the waste into fibres suitable for concrete reinforcement requires only simple shredding equipment and the overall operational cost is very low. Since the reinforcing fibres can be added to the concrete mix using the existing concrete mixing equipment, the resulting benefits will far offset the slight increase in cost. The use of recycled waste fibres in FRC could improve the performance and reliability of concrete structures while at the same time reduce or eliminate the need to dispose of the material in landfills.

One possible application of such FRC is for highway construction. A rough estimate indicates that 0.3 million tons of carpet waste would be consumed if 2 vol% carpet waste fibre is added to the concrete for the construction of 1000 Km of highways. Since cracking, spalling and scaling types of infrastructure 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.

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 not attacked by the alkalinity of Portland cement [1, 13], and so are expected to be very durable in concrete. In fact, the extremely low rate of degradation of carpet waste has contributed to the problem of disposing of it in landfills, since it may take centuries for the waste to decompose. The SBR (styrene–butadiene latex rubber) component in the carpet waste is the same in chemical structure as the styrene–butadiene latex polymer used in latex modified cement, and the SBR is not expected to degrade in concrete.

The carpet waste fibres were supplied by a waste recycling company and were used in this study in the "as-is" state. Highest FRC toughness can only be achieved when the reinforcement parameters, such as fibre size, strength and fibre matrix bond properties, are optimized [14, 15]. An approximate expression relating these quantities for fracture energy optimization is given by:

$$L_f = 1.2L_c$$

where L_f is the fibre length and L_c is the critical length of fibre pull-out, defined as the maximum embedded length of a fibre segment that can be pulled-out without rupture. L_c can be calculated from the fibre breaking load (P_{break}), pull-out force (P) and the embedded length (L) assuming a constant interfacial bond strength:

$$L_c = \frac{P_{\text{break}}}{P}L$$

For fibres from waste material, the size and properties may vary considerably from one type of fibre to another (e.g. face yarn, backing fibre), and they also depend on the source of the waste material. Estimating the optimal lengths for the face yarn and the backing fibre would none the less provide useful information for setting the disassembly and cutting parameters so that the dominant fibre length for the recycled fibres would be close to the optimal value. Toward this end, a direct fibre pull-out test from a mortar matrix (weight ratio for cement/sand/water = 1:2:0.5) was conducted on typical carpet face and backing fibres, and on the FiberMesh® fibre, all in continuous form. The face yarn is a textured nylon 6.6 yarn and the backing fibre is a polypropylene tape yarn. The test is illustrated in Fig. 15. It was performed on an Instron testing machine at 5 mm min^{-1}. Linear densities of the fibres were determined experimentally. The results are summarized in Table II.

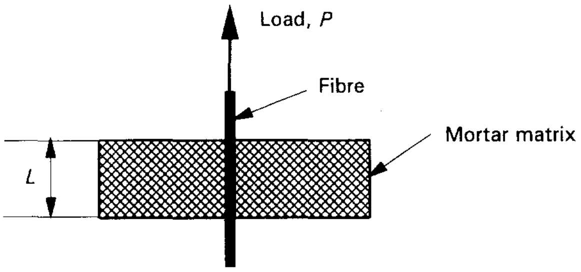


Figure 15 Schematic illustration of the fibre pull-out test.

TABLE II Fibre pull-out test results

Fibre	Fibre Mesh® PP	Carpet face yarn	Carpet backing fibre
Linear density (tex*)	295	313	53
Breaking load, P_{break} (N)	100.5	77.2	20.6
Embedded length, L (mm)	15.7	11.9	6.2
Number of specimens	8	6	6
Pull-out load, P(N)	65.3	38.6	12.4
P/L (N mm^{-1})	4.1	3.2	2.0
Calculated L_c (mm)	24.5	24.1	10.2
Optimal L_f (mm)	29	29	12
Actual length used (mm)	19	10–25	10–25

*1 tex = 1 g per 1000 m of fibre.

It can be seen that the actual length of the FiberMesh® fibre used in this study (19 mm) is much lower than the optimal length (29 mm), and as a result all the fibres bridging a crack in the FRC would be pulled-out without rupture. This was indeed observed in all the failed specimens (see also Fig. 11). Although fibre pull-out does absorb more energy than fibre rupture, in general, a complete pull-out without rupture indicates that the strength of the fibres is not fully utilized. Increasing the fibre length to 29 mm, or increasing the fibre matrix bond strength, could increase the pull-out resistance and thus also the toughness of the FRC. Modifying fibre surface coating (sizing agent) or crimping the fibres are among the possible ways to control the fibre/matrix interfacial properties.

The predicted optimal fibre lengths for recycled carpet waste fibres are 29 mm for the face yarn and 12 mm for the backing fibre. The actual fibre lengths used were widely distributed (not uniform), and typically 10–25 mm. Fibre pull-out was observed as the predominant mode. For better performance, the waste-to-fibre conversion process should be improved such that the fibre length could be maintained within a narrow range ca. 20 mm. The maximum fibre length should also be limited to 30 mm to avoid difficulties in mixing. Further studies are needed to verify the benefits of using such length-controlled recycled fibres.

8. Conclusions

A large amount of carpet waste is disposed of in landfills each year. This not only poses economical and environmental problems to the fibre/textile industry, it also represents a severe waste of resources because the waste material can prove to be valuable for certain applications. This study focused on the use of carpet waste fibres in fibre reinforced concrete and demonstrated that such reinforcement can effectively improve the shatter resistance, toughness and ductility of concrete. Such improvements in concrete performance can be beneficial for many applications, since many signs of concrete structure deterioration are associated with the brittle nature of ordinary concrete. It is estimated that ca. 0.3 million tons of carpet waste could be added to concrete used for the construction of 1000 km of highways.

The strengths of the FRC were tested in compression, flexure and splitting tension. FRC specimens in all the tests failed in a shatter contained manner in contrast to plain concrete, which failed catastrophically. The strength values in these tests were basically not affected by the fibre reinforcement. It appeared that the size of specimens for the splitting tensile test (76 mm in diameter) was not adequate and a larger size is needed for such a test.

The flexural toughness of FRCs with FiberMesh®, as well as carpet waste fibres up to 2 vol %, were evaluated by a four-point bending test and the TIs according to ASTM C 1018, and Wang and Backer [6], were reported. The two types of waste fibres generally gave a similar toughening effect, and at 2 vol % they provided a reinforcement better than that with 0.5 vol % of virgin polypropylene FiberMesh® fibres.

A reduction of drying shrinkage due to fibre reinforcement was observed, and the amount of reduction was in the range of 15–30% after 500 h of drying.

The carpet waste fibres used exhibited a wide range of length distribution, ranging from less than 10 mm to 25 mm. Based on a pull-out test and an optimization analysis, a better reinforcement effect is predicted if a consistent length, close to 20 mm, for the recycled fibres is obtained. A better effect is also predicted for the FiberMesh® fibres if the length is increased to 29 mm or if the fibre/matrix interfacial bond strength is increased.

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