WASTE MATERIALS AND THEIR GEOTECHNICAL/GEOENVIRONMENTAL APPLICATIONS

PROCEEDINGS OF THE 2ND ANNUAL GREAT LAKES GEOTECHNICAL/GEOENVIRONMENTAL CONFERENCE

MAY 20, 1994
PURDUE UNIVERSITY
W. LAFAYETTE, INDIANA

EDITED BY

RODRIGO SALGADO
SCHOOL OF CIVIL ENGINEERING
PURDUE UNIVERSITY
W. LAFAYETTE, INDIANA

Shrinkage Behavior of Cementitious Composites with Recycled Fiber

Hwai-Chung Wu, Yun Mook Lim, and Victor C. Li
Advanced Civil Engineering Materials Research Laboratory
Department of Civil and Environmental Engineering
University of Michigan, Ann Arbor, MI 48109

Abstract

In this paper, recycled fibers from both carpet industry waste and used tire are used in reinforcing brittle concrete. Shrinkage characteristics of such cement-based composites is studied. Free shrinkage as well as restrained shrinkage using a ring-type specimen is measured. In the latter tests, cracking phenomenon and crack width are continuously monitored. Significant reduction in crack width can be expected due to fiber bridging leading to much improved durability. The role of each recycled fiber is discussed, along with experimental findings. Some of these recycled materials are expected to have broad applications in the building and construction industries based on economic and performance advantages, at the same time solving disposal problems.

Introduction

Recently, there has been much attention on the rapidly deteriorating infrastructure. The main cause of the decay of infrastructure is the deterioration of the materials used in the construction and repair of the structures. In many types of infrastructure, such as highway and airport pavement, cracking behavior is the most important factor for the determination of durability and life time of structures. For example, the control of the crack spacing and width is the main design concern in continuously reinforced concrete pavement (McCullough, 1981). This cracking behavior is related to environmental strain due to either dry shrinkage or thermal change in concrete structures with restrained boundary condition. Such shrinkage cracking is a major concern for concrete, especially for large surface-to-volume ratio structures such as highway pavement, slabs for parking garages, and walls (Shah et al., 1992).

Microcracks are developed in the early age of structures due to various shrinkage mechanisms with the restrained boundary condition of structures and these cracks might be an initial point of crack growth during the life time of a structure. Also, this crack growth causes several problems in a reinforced concrete structure: durability problems related to the corrosion of rebars, spalling of structure surface, and much increased permeability through the cracks, etc. Thus, the control of the shrinkage cracking behavior in cementitious materials is considered an important factor for long term structural performance.

In the past, research was conducted on the shrinkage behavior of ordinary concrete and reinforced concrete structures. Recently, attention has been focused on fiber reinforced cementitious composites (Krenchel and Shah, 1987, Grzybowski and Shah, 1990, Shah et al., 1992, Banthia et al., 1993). Typical parameters that affect shrinkage of concrete are aggregate contents, water-cement ratio, curing condition, environmental condition, volume-to-surface ratio of structures (Mindess and Young, 1981). For fiber reinforced concrete, the additional variables are fiber type, fiber volume fraction, and aspect ratio of the fibers (Balaguru and Shah, 1992). It was found that the effect of discrete fibers are more sensitive in reducing shrinkage cracking rather than in reducing free shrinkage, although reports of 10 - 25 % reduction in free shrinkage in cementitious composites have been reported by addition of steel fibers (Malmberg and Skarendahl, 1978, Balaguru and Shah, 1992). Shrinkage cracking can be significantly reduced with the increase of fiber volume fraction in cementitious composites as expected (Bentur and Mindess, 1990).

In the above mentioned studies of shrinkage behavior of FRCs, all composites were reinforced with various types of new virgin fibers including polypropylene and steel. However, data on the shrinkage property of concrete reinforced with recycled waste fibers are much scant. Many industrial wastes can be recycled and utilized in building and highway construction. At present, most of these wastes are disposed of in landfills which is a great environmental concern. For example, the waste generated by the carpet industry and from used carpet is estimated at about 2 million tons per year (Wang et al., 1993). Useful fibers (mainly polypropylene and nylon) can be retrieved from these waste. Used tire is another example. About 275 million tires are disposed of annually, and 3 billion used tires have accumulated in waste piles across the nation (National Research Council, 1991). In addition to granulated rubber particles which have been using in asphalt pavements with some success, recycled tire cord (such as nylon, polyester, and Kevlar) and rubber strip still await future utilization. These recycled fibers can contribute to much improved composite properties when adequate fiber length and interfacial property are achieved. This property-improvement viewpoint different from mere consumption of otherwise wastes can be efficiently fulfilled through guidelines obtained from micromechanical model (Li, 1992). These recycled materials are expected to provide wide applications based on economic and performance advantages, at the same time solving disposal problems.

In this paper, the free shrinkage and the shrinkage cracking behavior of recycled fiber composites are examined as a function of different types of recycled fibers and their surface modification by plasma treatment. Flexural strengths of various recycled fiber composites are compared and discussed. Further recommendation on optimum fiber geometry and surface condition for each fiber type will be reported in a companion paper.

Experimental Program

In this study, total four types of fibers are used as reinforcement in ordinary concretes. Three types of recycled fibers with and without additional surface modification by plasma treatment are used to indicate the effectiveness of each recycled fiber. Also, one type of ordinary hooked end steel fiber (ZL 30/50, 30 mm long and 0.5 mm diameter) is used for comparison. This type of steel fiber has been used for concrete reinforcement in the construction industry. The recycled fibers are obtained from carpet waste and disposed tires. The fibers from carpet waste contain backing fibers (usually polypropylene), latex adhesive particles, and small amount of face fibers. The fibers retrieved from disposed tires have two types: one is called tire fabric (70% polyester, 15% nylon, 15% glass and some rubber residues) which was originally tire cord and the other is called tire-rubber strip which was the main component of tires. All fibers used are shown in Figure 1. The carpet fiber and tire fabric were treated separately by air gas plasma treatment at a flow rate of 40 ml/min. and power level of 150 W for 10 minutes.

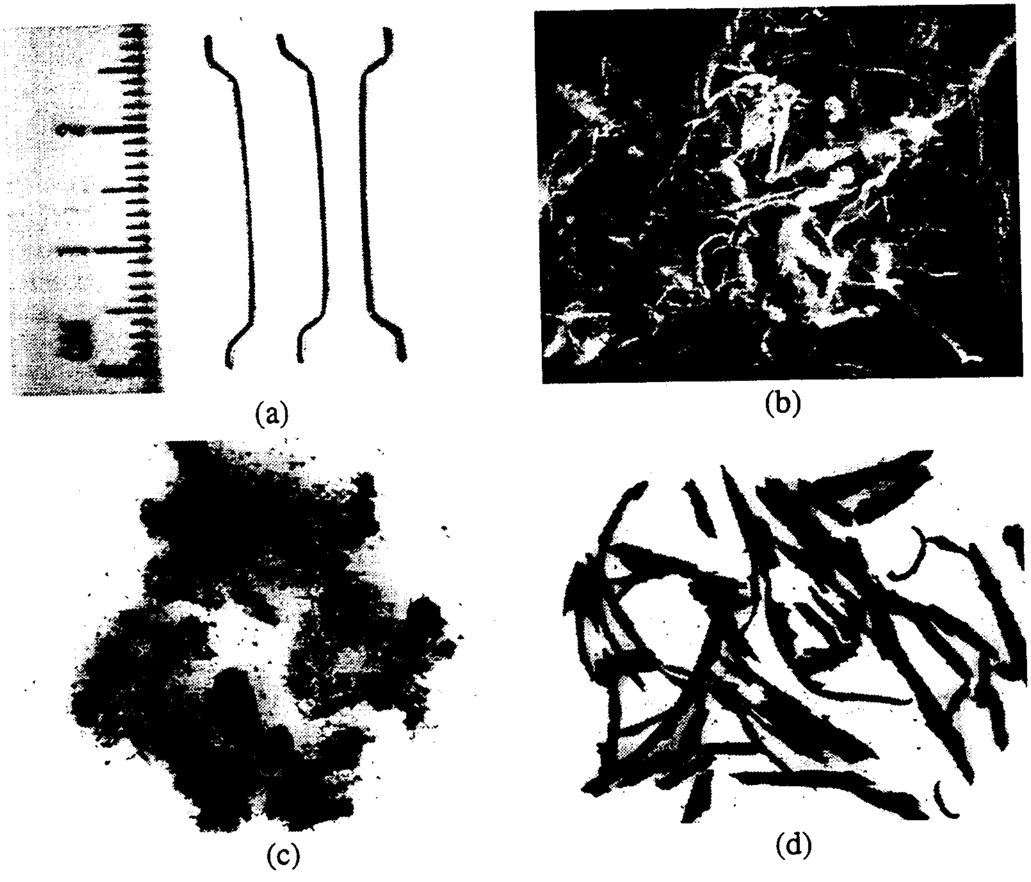
(a) (b) (c) (d)

Figure 1. All fibers used in this study (same scales) (a) steel (b) carpet (c) tire fabric (d) tire rubber strip.

Recycled fiber volume fractions in each composite are fixed at 2%, whereas steel fiber is used at 1% volume fraction. Ordinary concrete with river sand and crushed aggregate (maximum size 9.6 mm, cement:sand:aggregate=1:1.72:1.72) is used as the matrix of the composites. The water to cement ratio is 0.45 and the compressive strength of this concrete is 50.0 MPa. Superplasticizer (3% by solid weight) is used in the recycled fiber composites to improve workability.

Free shrinkage and restrained shrinkage are measured in this study. The free drying shrinkage test follows the standard test method, ASTM C 596-89 and ASTM C 157. Four specimens (25.4 mm x 25.4 mm x 285.7 mm) are prepared for each composite. However, there is no standardized test method for the restrained shrinkage test. Thus, a ring test, similar to the ring-type specimens used in a restrained shrinkage study by Grzybowski and Shah (1990), is adopted in this study. The dimensions of the specimen are shown in Figure 2. Both specimens (free shrinkage and ring specimens) were demolded after 24 hours of placing and cured for two days under 100% humidity condition. The specimens were then stored in an environmental chamber with constant temperature and relative humidity control. The temperature and relative humidity per ASTM C 157 are 75°F and 50%, respectively.

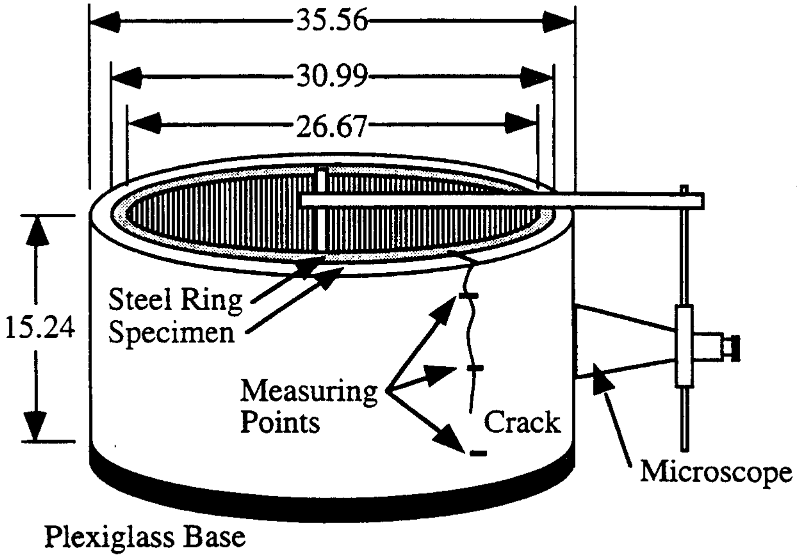

Figure 2. Specimen and measuring device for ring test

In free shrinkage test, to measure the length change of the free shrinkage specimen a comparator with 0.0001 in. units is used. In ring test, a microscope with 100x magnitude is used to measure the crack width on the side surface. Three points (1.27 cm, 7.62 cm, and 13.97 cm from the top of specimen) are measured along a crack and the average values are reported. The microscope is mounted on the ring specimen with a specially designed fixture (see Figure 2).

The flexural test in this study follows the standard test method as described in ASTM C78-75, standard test method of flexural strength of concrete (using simple beam with third-point loading). The total length, height, and width of the beam are 355.6 mm, 101.6 mm, and 76.2 mm, respectively. The mid-span length, 101.6 mm, is one-third of the span length, 304.8 mm. All flexural specimens, two for each composite types, were moisture cured for 24 hours before demolding, and cured in room temperature water. The age at testing was 28 days. The beam deflection was measured using high sensitivity displacement gauge attached at the middle of beam on the bottom surface.

Results and Discussion

Workability

The workability of the recycled fiber composites was similar to that of concrete, except for the recycled carpet fiber composites with and without surface treatment. There are no quantitative data for measurement of workability, but much poor workability of the carpet fiber composites can be easily noticed. The reason might be high water absorption by the carpet fibers, leading to reduced w/c ratio.

Free Shrinkage

The amount of free shrinkage is measured for each composite at 4, 7, 11, 17, 24, 31, and 38 days after exposure in controlled environmental condition (see Figure 3). The shrinkage strain values at 27 days (including 3 days curing) of various composites are shown in Table 1. The free shrinkage behavior of concrete in this study agrees well with literature data. The free shrinkage of SFRC (V_f=1%) is about 7 % lower than that of concrete, and this result is similar to that of Malmberg and Skarendahl (1978). On the other hand, the free shrinkages of the recycled fiber composites are 22 - 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 addition of the recycled fibers. The weight increase of wet specimen (soaked in water for 30 hours) compared to dry specimen (conditioned in oven for 24 hours at 110°C) of recycled fiber composites specimens is higher than that of concrete or SFRC (see Table 1).

Table 1: Free shrinkage of concrete and FRCs (age=27 days)

Material	Fiber Type	V_f (%)	Shrinkage (10^{-6})	W* (%)
Concrete	-	0	765.0	6.82
SFRC	Steel	1	711.3	6.02
CFRC	Carpet	2	938.5	-
PCFRC	Carpet/P*	2	1105.0	7.64
TFRC	Tire fabric	2	1200.0	7.23
PTFRC	Tire fabric/P*	2	1051.3	7.15
TRFRC	Tire rubber	2	1165.0	7.57

(P* : Plasma treated, W* : Weight increase when wet)

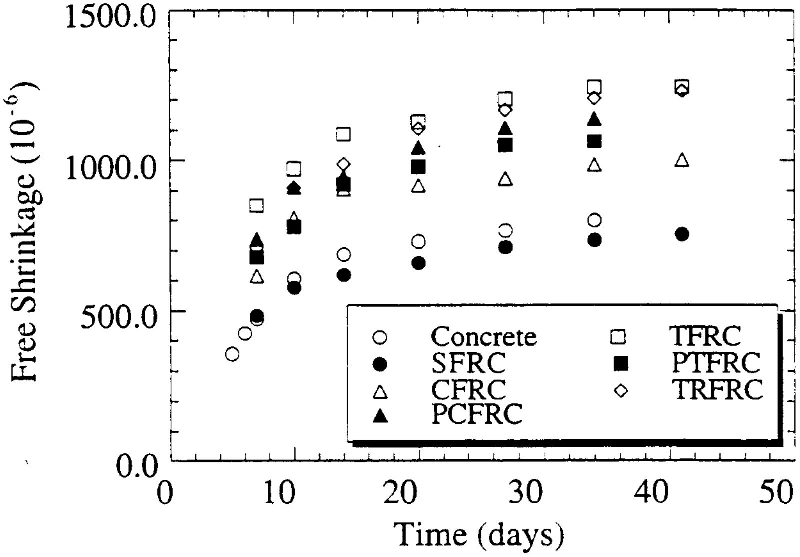

Figure 3. Free shrinkage strains in concrete and FRCs

The surface modification by plasma treatment decreases free shrinkage in the recycled tire fabric composites, but it gives opposite results to the recycled carpet fiber composites. Usually, the surface modification by plasma treatment can improve bond strength of virgin fibers (Li, et al., 1994). However, the effect of plasma treatment is not yet clear for recycled fibers. Many different material residues are present in recycled fibers, and this mixity is more significant in the recycled carpet fibers than others.

Restrained Shrinkage Cracking

Restrained shrinkage cracking behavior of various composites is illustrated in Figures 4 and 5, and summarized in Table 2. Figure 4 illustrates the total crack width in each specimen, whereas Figure 5 shows the maximum crack width development with respect to time. In Table 2, the maximum crack width, the total crack width, the total number of cracks, the number of through cracks and the average crack spacing are reported. Here, through crack means that the crack goes through from the top to the bottom of the specimens.

As expected, the crack widths are significantly reduced in the recycled fiber composites except TRFRC. The crack width of TRFRC is much smaller than that of concrete before 12 days, but the crack width was sharply increased after 14 days and became as wide as that of concrete (see Figures 4 and 5). This sharp-opening phenomenon cannot be found in any other recycled fiber composites and it might be explained by the high Poisson's ratio of tire rubber. The tire rubber fibers can be completely separated from the matrix, and pulled-out without frictional resistance because of the large reduction of the fiber cross section due to the high Poisson's ratio of rubber (about 0.5) during the tensile loading of the fibers. Thus, the loss of fiber bridging action, due to complete separation of the fiber from the matrix, occurs at a certain point.

In the recycled carpet fiber composites, the crack width and spacing are evenly distributed in the both cases (with and without plasma treatment). However, the plasma treated case has a slightly larger crack width and has more through cracks. This result is consistent with the free shrinkage behavior, since the PCFRC has a 18% increase in free shrinkage compared to the CFRC (see Table 1).

In the tire fabric composites, the crack width is comparable with the SFRC, even though the free shrinkage is much higher than that of SFRC (70% higher). This reduction of crack width in TFRC and PTFRC can be explained by the microscopic surface observation. In both cases, randomly distributed very fine cracks (less than 10 μm) are observed. There is almost no such cracks on the concrete and SFRC surface, but there are some microcracks in the other recycled fiber specimens to a lesser extent. These microcracks are most significant in the TFRC and PTFRC cases. PTFRC gives even smaller crack widths compared to TFRC. Again, this is consistent with the free shrinkage behavior (PTFRC is 12% less than TFRC).

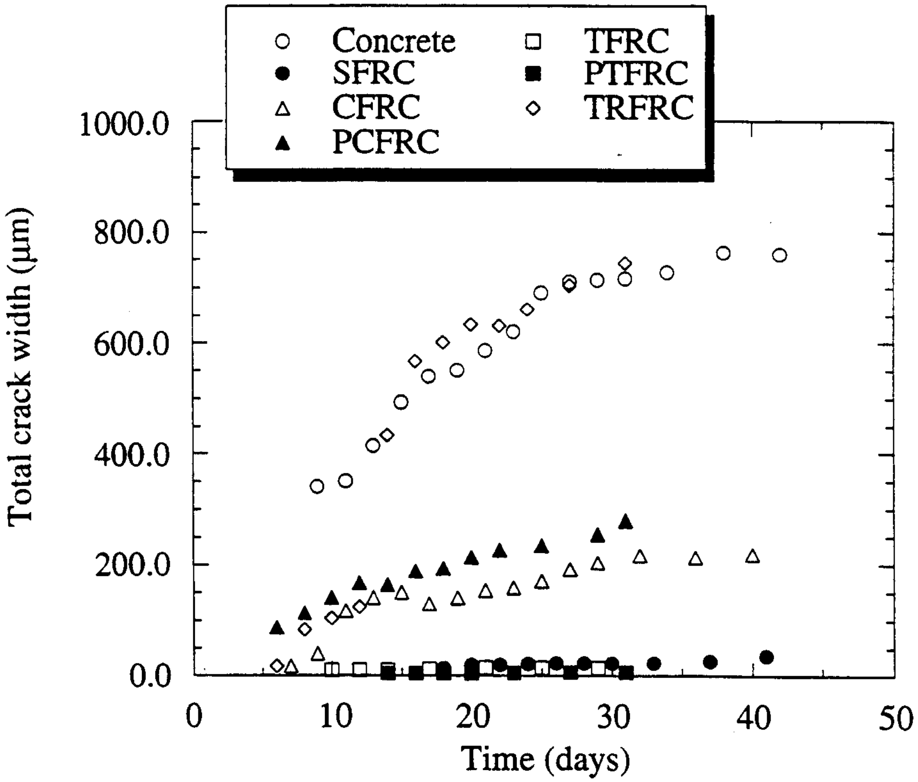

Figure 4. Total crack width in restrained shrinkage specimens.

Table 2: Restrained shrinkage test results (age=27 days)

Material	$\omega_{max.}$(μm)	ω_t (μm)	N_c	N_t	$S_{avg.}$(cm)
Concrete	715	715	1	1	-
SFRC	17	23	2	0	55.86
CFRC	55	170	4	1	27.93
PCFRC	83	228	4	3	27.93
TFRC	15	15	1	0	-
PTFRC	7	7	1	0	-
TRFRC	633	633	1	1	-

($\omega_{max.}$: maximum crack width, ω_t : total crack width, N_c : no. of cracks, N_t : no. of through cracks, $S_{avg.}$: average spacing of cracks)

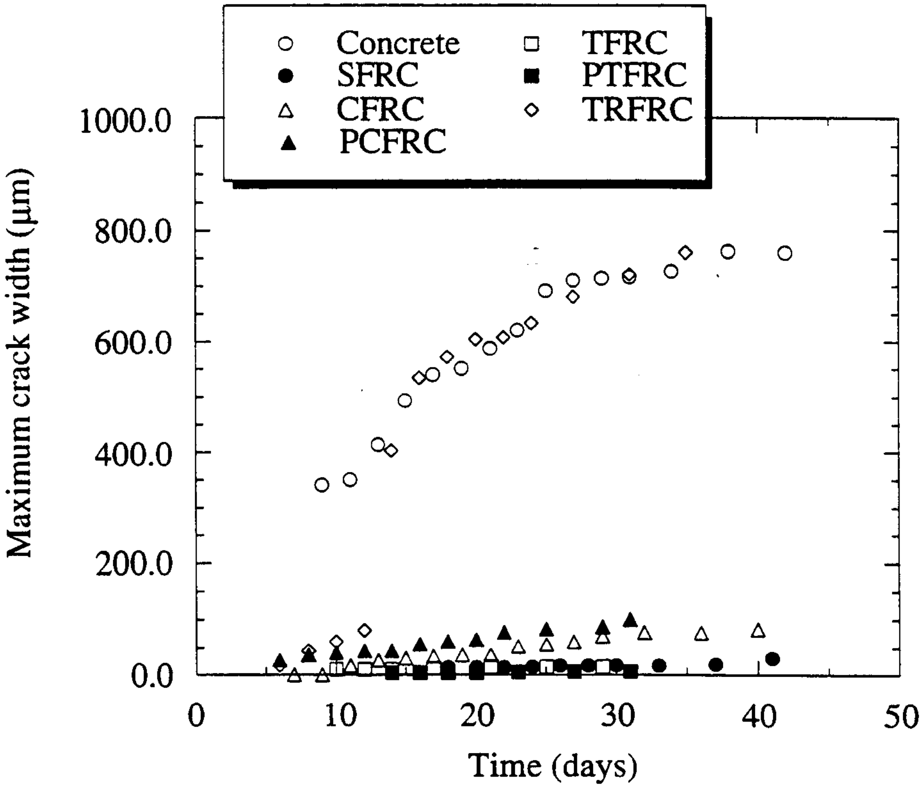

Figure 5. Maximum crack width in restrained shrinkage specimens.

Flexural Strength and Toughness Index

The average flexural strength of the recycled fiber composites is tabulated in Table 3, together with toughness indices. There is no significant difference in flexural strength between the concrete and recycled fiber composites, except TRFRC which is 30% lower compared to concrete. The major difference between the recycled fiber composites and concrete is toughness indices (Wang et al., 1993), an indication of toughness improvement as a result of the post-cracking behavior. Catastrophic ruptures were observed in the concrete, but some "ductility" was noticed in the recycled fiber composites (see Figure 6). TRFRC shows a much lower ductility compared to the other composites. This inefficient reinforcement might be caused by low elastic modulus of the fibers and the Poisson's effect mentioned above. Therefore, the fibers were pulled-out almost frictionlessly with little contribution to the toughness improvement. Nevertheless, the TRFRC specimens are still held in one piece after releasing the applied load. When comparing TFRC and CFRC, higher toughness is observed in CFRC. This is probably due to the much shorter fiber length of the recycled tire fabric, leading to shorter fiber pull-out distance after cracking.

Table 3: Flexural strength and toughness indices.

Material	σ_f(MPa)	I_5	I_{10}
Concrete	4.40	1.00	1.00
CFRC	4.50	3.35	5.74
TFRC	3.95	3.10	4.47
TRFRC	3.10	2.29	2.49

Further Discussion

Cracking in concrete structures cannot be avoided because of the brittle characteristic of concrete materials. In practice, allowable crack width is limited to a given range, according to specific applications, by using steel reinforcement in order to improve durability of the reinforced concrete structures. The desirable crack width should be less than 0.1 mm for water-retaining structures and 0.4 mm for structures in dry air condition (ACI Committee 224, 1972). Additionally, the allowable crack width in rigid pavement systems is 0.8 mm (0.03 in), permitting load transfer between crack surfaces by aggregate interlocking. The maximum crack widths in the concrete and TRFRC specimens are close to the allowable crack width for pavements and are several times higher than the allowable crack width for reinforced concrete structures. It should be noted that the maximum crack width in this study cannot be directly compared with the allowable crack width of reinforced concrete structures since there is no steel reinforcement in our shrinkage specimens. On the other hand, our shrinkage specimens are only environmentally loaded, but not mechanically loaded. The maximum crack width in the other recycled fiber composites is one or two order magnitude smaller than the allowable crack width for pavement systems.

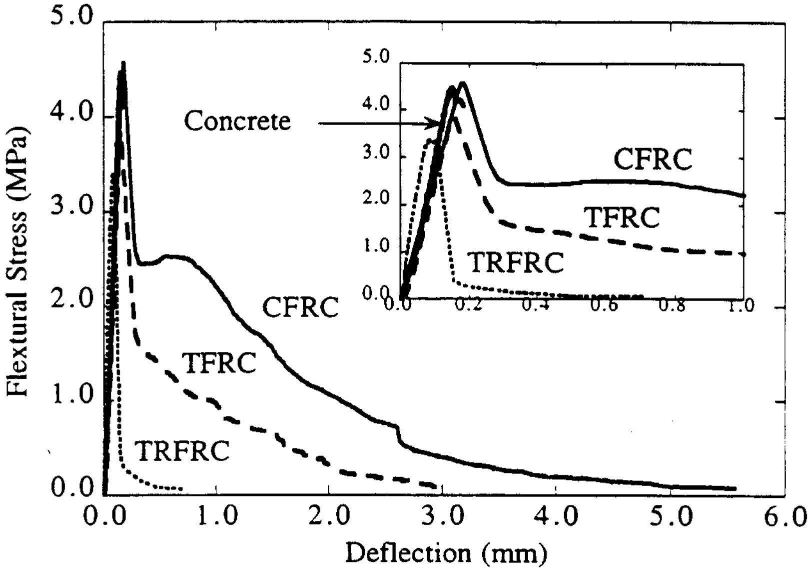

Figure 6. Typical flexural stress and deflection curves of composites (insert shows initial portion).

Furthermore, water flow rate is highly sensitive to crack width under a constant fluid pressure (Tsukamoto, 1991). In Tsukamoto's study, the flow rate was found to scale with the third power of crack width. For example, the maximum crack width of a recycled fiber composite is one-tenth of concrete, water flow rate of the concrete is about 1000 times larger than that of the composite. Even when this composite has more cracks, say five cracks, versus one crack in the concrete per same area, the flow rate in the concrete is still 200 times larger if we assume flow rate is increased linearly with the number of cracks. This aspect, obviously, requires further study. Water flow rate can be related to permeability of concrete structures. Especially, permeability of a pavement is of importance for long term performance, because permeated water through a crack can destroy the stability of subbase soil under a pavement. A dramatically reduced crack width, hence low permeability, can have a significant effect on long term behavior of concrete structures including pavement systems.

The preliminary results of the present research suggest that the addition of some recycled material in fiber form may aid in certain performance of the recycled fiber reinforced concrete. Additional research should be conducted on tailoring the properties of fiber, matrix, and interface so that desirable shrinkage behavior of recycled fiber composites can be achieved with minimum fiber volume fractions. This performance driven design approach has been found effective in structural applications (Li, 1992). Specifically, the influence of matrix additives (such as silica fume, fly ash, and shrinkage reducing agent), fiber length, and fiber surface modification on the shrinkage cracking property of recycled fiber composites should be studied.

Summary

In this study, the shrinkage behavior of three types of recycled fibers composites, i.e. from carpet, tire cord, and tire strip, was investigated and compared with that of ordinary concrete and commonly used steel FRC. The free shrinkages of the recycled fiber composites are found to be 22 - 57 % higher than that of concrete, whereas SFRC(V_f=1%) is 7% lower than that of concrete. Even though the free shrinkages are higher in the recycled fiber composites, the maximum crack widths in the restrained ring specimens of such composites, except TRFRC, are one or two order magnitude smaller than that of concrete. In particular, the tire fabric composites show a similar crack width to the SFRC despite of a 70% increase in free shrinkage. The fiber surface modification by an air plasma treatment gives a 12% reduction of free shrinkage, and 53% reduction of the maximum crack width in the ring specimens for the recycled tire fabric composites. On the contrary, the same treatment increases 18% and 51% respectively for the recycled carpet fiber composites. Finally, the flexural strengths of the recycled fiber composites, except the TRFRC, is shown to be similar to that of concrete with improved toughness. This behavior is commonly observed for concrete reinforced with new virgin fibers.

Acknowledgment

The fibers used in this study were supplied through courtesy of Baker Rubber Inc. (tire fabric and tire strip) and Central fiber Inc. (carpet waste fiber).

References

1. ACI Committee 224, "Control of Cracking in Concrete Structures," **Journal of the American Concrete Institute**, Vol. 69, No. 12, 1972, pp. 717-753.
2. ACI Committee 544, "State-of-the art report on fiber reinforced concrete," 544.1R-82, **American Concrete Institute**, Detroit, 1986
3. Balaguru, P.N., and Shah, S.P., **Fiber-Reinforced Cement Composites**, McGraw-Hill Inc., 1992.
4. Banthia, N., Azzabi, M., and Pigeon, M., "Restrained shrinkage cracking in fiber-reinforced cementitious composites," **Materials and Structures**, Vol. 26, 1993, pp. 405-413.
5. Bentur A., and Mindess, S., **Fiber Reinforced Cementitious Composites**, Elsevier Applied Science, 1990.
6. Grzybowski, M., and Shah, S.P., "Shrinkage cracking of fiber reinforced concrete," **ACI Materials Journal**, V. 87, No. 2, 1990, pp. 138-148.

7. Krenchel, H., and Shah, S., "Restrained shrinkage tests with PP-fiber reinforced concrete," **Fiber Reinforced Concrete Properties and Application**, SP 105, American Concrete Institute, Detroit, 1987, pp. 141-158.
8. Li, V.C., "Performance driven design of fiber reinforced cementitious composites," in **Proceeding of 4th RILEM International Symposium on Fiber Reinforced Concrete**, Ed. R. N. Swamy, Chapman and Hall, 1992, pp. 12-30.
9. Li, V.C., Wu, H.C., and Chan, Y.W., "Effect of Plasma Treatment of Polyethylene Fibers on Interface and Cementitious Composites Properties", in preparation, 1994.
10. Malmberg, b., and Skarendahl, A., "Method of studying the cracking of fibre concrete under restrained shrinkage," **Testing and Test Methods of Fibre Cement Composites**, ed. Swamy, R.N., Proc. RILEM Symp., The Construction Press, UK 1978, pp. 173-179.
11. McCullough, B. F., "Criteria for the design and construction of continuously reinforced concrete pavement," **Concrete Pavements**, edited by Stock, A. F., Elsevier Applied Science, 1988, pp. 279-318.
12. Mindess, S., and Young, J.F., **Concrete**, Prentice-Hall Inc., Englewood Cliffs, N.J., 1981.
13. National Research Council, "Program Announcement for the Innovations Deserving Exploratory Analysis (IDEA) Program", **Strategic Highway Research Program**, June, 1991.
14. Shah, S.P., Karaguler, M.E., and Sarigaphuti, M., "Effective of shrinkage-reducing admixtures on restrained shrinkage cracking of concrete," **ACI Materials Journal**, V. 89, No. 3, 1992, pp. 289-295.
15. Tsukamoto, T., "Tightness of fiber concrete," in **Darmstadt Concrete**, V. 5, 1990, pp. 215-225.
16. Wang, Y., Cho, B.S., and Zureick, A.H., "Fiber reinforced concrete using recycled carpet industrial waste and its potential use in highway construction," **In Proceedings of the Symposium on Recovery and Effective Reuse of Discarded Materials and By-Products for Construction of Highway Facilities**, October 19-22, 1993, Denver, Colorado.
17. Wang, Y., Li, V.C., and Backer, S., "Tensile failure mechanisms in synthetic fiber reinforced mortar," **Journal of Materials Science**, Vol. 26 No. 24, 1991, pp. 6565-6575.