ELSEVIER

1359-8368(95)00020-8

Composites: Part B **27B** (1996) 269–274

1359-8368/96/$15.00

Low-drying-shrinkage concrete containing carbon fibers

Pu-Woei Chen and D. D. L. Chung
Composite Materials Research Laboratory, State University of New York at Buffalo, Buffalo, NY 14260-4400, USA
(Received January 1995; accepted May 1995)

This paper provides a low-drying-shrinkage concrete (with fine and coarse aggregates) that is practically attractive when strength (compressive and flexural), flexural toughness, freeze–thaw durability, chemical attack resistance and cost are all considered. The use of short carbon fibers (just 0.19 vol%), together with silica fume, in concrete results in an 84% decrease of the drying shrinkage strain at 14 days of moist room curing; the shrinkage strain is just 1.9×10^{-5} at 14 days. The fibers dominate the silica fume in lowering the drying shrinkage and increasing the flexural toughness. However, both fibers and silica fume contribute to lowering the drying shrinkage and increasing the flexural strength, toughness and freeze–thaw durability. On the other hand, the fibers decrease while the silica fume increases the compressive strength and chemical attack resistance, so the combined use of fibers and silica fume is recommended. The adverse fiber effects are associated with an air content increase.

(Keywords: concrete; cement; carbon fibers; drying shrinkage; composite; mechanical)

INTRODUCTION

Drying shrinkage is one of the main causes of cracks in large concrete structures, such as floors and dams. To alleviate this problem, shrinkage-compensating concrete[1,2] is available. This concrete involves the use of expansive cement, which, when mixed with water, forms a paste that, after setting, tends to increase in volume. The expansive cement is used to compensate for the volume decrease due to shrinkage. Although shrinkage-compensating concrete has been available for over 20 years, its usage remains limited. This is partly because of the need to allow for the concrete to expand prior to the drying shrinkage—a need which limits the applications and adds to the inconvenience of usage. Moreover, shrinkage-compensating concrete requires more water than portland cement due to the fact that the expansion is associated with the formation of ettringite or high sulfate calcium sulfoaluminate. As a result of the water requirement, curing needs to be carried out in an enclosed environment, thus adding to the inconvenience of usage. A better solution to the drying shrinkage problem is concrete that does not expand or shrink. In this paper, by the use of short carbon fibers and silica fume, concrete with a drying shrinkage equal to 16% of that of conventional concrete is provided. The fibers rather than silica fume is the main ingredient that gives rise to the low drying shrinkage.

Previous work on the use of additives to decrease the drying shrinkage had involved the use of fibers (short) and silica fume[3–8]. For example, the use of 3 mm long carbon fibers in the amount of 1 vol.% in cement (without aggregate) resulted in a drying shrinkage strain of 1.3×10^{-4} at 14 days of curing, compared to a drying shrinkage strain of 2.5×10^{-4} at 14 days for the corresponding case without fibers[3]; the use of steel fibers in the amount of 2 vol.% in concrete (with fine and coarse aggregates) resulted in a drying shrinkage strain of 4×10^{-4} at 20 days after the initial 7 days, compared to a value of 6×10^{-4} for the corresponding case without fibers[5]; little effect was reported for steel or polypropylene fibers in the amount of 1 vol.% on the drying shrinkage strain of concrete (with fine and coarse aggregates)[6]; negligible effect was reported for cellulose or polypropylene fibers in the amount of 0.5 vol.% on the drying shrinkage strain of concrete (with fine and coarse aggregates)[7]; the use of silica fume (5–30% replacement of the cement) in concrete (with fine and coarse aggregates) resulted in a drying shrinkage strain ranging from 1.8×10^{-4} to 2.4×10^{-4} at 28 days, compared to a value of 2.3×10^{-4} for the corresponding case without silica fume[8]. Moreover, the shrinkage crack width was reported to be decreased by the addition of 0.1 vol.% polypropylene or acrylic fibers[9] or carbon fibers (from 1 to 3 vol.%)[10]. Latex addition was reported to decrease the drying shrinkage of carbon fiber reinforced mortar by about 10%[11].

As shown in ref. 3, the drying shrinkage decreases with increasing carbon fiber volume fraction. However, the cost also increases with the fiber content. Thus, for the concrete to be economically viable, the fiber content must be minimised. This is why this work is concerned with a fiber content of just 0.19 vol.%. Moreover, this work is concerned with concrete rather than mortar or cement paste, because of concrete's practical importance. The objective of this paper is to provide a low-drying-shrinkage concrete that is practically attractive when cost, strength (compressive and flexural), flexural toughness, freeze–thaw durability and chemical attack resistance are all considered.

EXPERIMENTAL

Raw materials

The short carbon fibers were pitch-based and unsized. The nominal fiber length was 5 mm. The fiber diameter and properties are shown in *Table 1*. The fibers were provided by Ashland Petroleum Co. (Ashland, KY).

The raw materials are shown in *Table 2*. Aggregate B is the fine aggregate (standard aggregate for masonry mortar, ASTM C114-81; 100% passed #4 standard sieve); Aggregate D is the coarse aggregate (#57 aggregate, ASTM C33-84; 100% passed 25 mm (1 in) standard sieve). The cement was Portland cement (Type I) from Lefarge Corp. (Southfield, MI). The methylcellulose was Methocel A15-LV from Dow Chemical (Midland, MI). Colloids 1010 (Colloids Inc., Marietta, GA) was a defoamer that needed to accompany methylcellulose. Both methylcellulose and silica fume (Elkem Materials Inc., Pittsburgh, PA) served to help disperse the fibers. The water reducing agent was a sodium salt of a condensed naphthalenesulphonic acid from Rohm and Haas Co. (Philadelphia, PA).

Table 1 Properties of carbon fibers

Filament diameter	10 μm
Tensile strength	690 MPa
Tensile modulus	48 GPa
Elongation at break	1.4%
Electrical resistivity	3.0×10^{-3} Ω cm
Specific gravity	1.6 g cm^{-3}
Carbon content	98 wt.%

Table 2 Raw materials for concrete

Water/cement = 0.50
Cement/aggregate B/aggregate D = 1 : 1.5 : 2.49 (by weight)
Fibers/cement = 0.5%; 0.19 vol.% fibers in concrete
Methylcellulose/cement = 0.4%
Silica fume/cement = 0.15
Colloids 1010 = 0.13 vol.%
Water reducing agent (TAMOL SN)/cement = 2%
Accelerating agents:
  Triethanolamine/cement = 0.06%
  Potassium aluminium sulphate/cement = 0.5%
  Sodium sulphate/cement = 0.5%

Mixing procedure

Methylcellulose was first dissolved in water. Then fibers were added and stirred. After that, Aggregate B, cement and silica fume were added. Subsequently the water reducing agent was added. Then the mixture was stirred with a Hobart mixer with a flat beater for ≈ 5 min. The accelerating agents (*Table 2*) were then added and then stirred for ≈ 3 min. After this, the mix was poured into a stone concrete mixer. Then Aggregate D was added and then mixed for ≈ 3 min. After pouring the mix into oiled molds, an external vibrator was used to decrease the amount of air bubbles.

Curing procedure

The specimens were demolded after 1 day and then allowed to cure in a moist room for various lengths of time.

Drying shrinkage

The dry shrinkage was investigated by measuring the specimen length change in accordance with ASTM C490-83a. The beam specimen size was 76.2 × 76.2 × 286 mm (3 × 3 × 11.25 in). The accuracy in the length change measurement was ±0.0025 mm (0.0001 in). *Figure 1* shows the plot of drying shrinkage strain *versus* curing time. Comparison of 1 and 2 and comparison of 3 and 4 (1, 2, 3 and 4 as defined in *Table 3*) in *Figure 1* give the effect of the fibers alone. Comparison of 1 and 3 and comparison of 2 and 4 give the effect of silica fume alone. It is thus clear that the effect of the fibers dominates, though both fibers and silica fume serve to lower the drying shrinkage at all curing ages. Comparison of 1 and 4 shows that the use of

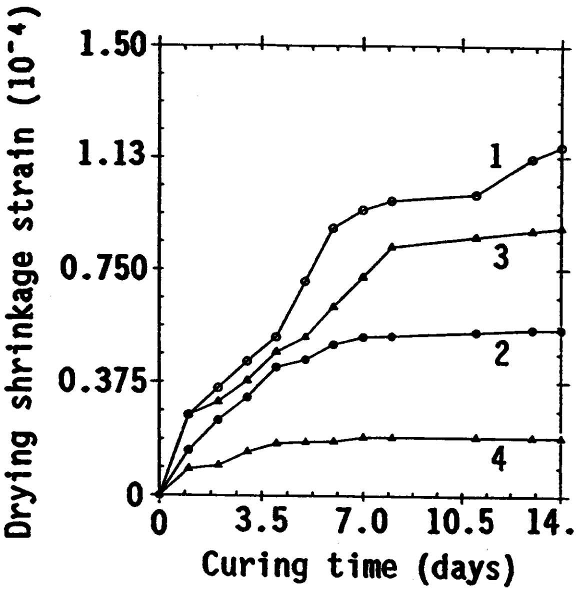

Figure 1 Drying shrinkage strain *versus* curing time for concrete curing in a moist room. (1), (2), (3) and (4) are as defined in *Table 3*

both fibers and silica fume decreases the drying shrinkage by 84% at 14 days of curing.

Flexural properties

Flexural testing was performed on all specimens by three-point bending (ASTM C348-80), with a span of 241 mm (9.5 in). The specimen size was 76.2 × 76.2 ×279 mm (3 × 3 × 11 in). Six specimens of each concrete type (labeled 1, 2, 3 and 4, as defined in *Table 3*) were used. The flexural toughness was calculated from the area under the load/deflection curve obtained in flexural testing, such that three specimens of each type of specimen were used. *Figure 2* shows the plots of flexural stress *versus* displacement during flexural testing of the four types of concrete (labelled 1, 2, 3 and 4 and defined in *Table 3*) after 7, 14 and 28 days of curing. These plots indicate that the high flexural toughness of type 4 after 14 days of curing is due to its high flexural strength, as well as its high ductility (strain at break). Comparison between types 2, 3 and 4 at 28 days of curing shows that the relatively high flexural toughness of type 2 is due to its high ductility. *Tables 3* and *4* list the flexural strength and flexural toughness respectively. Both the fibers and silica fume serve to enhance both the flexural strength and flexural toughness, but the effect on the flexural toughness is dominated by the fibers.

Compressive strength

The cylindrical specimen size used in the compressive tests was 102 mm (4 in) diameter × 203 mm (8 in) length (ASTM C39-83b). Six compression specimens of each concrete type were tested. *Table 5* lists the compressive

Table 3 Flexural strength of concrete at different curing ages: (1) plain concrete; (2) with fibers, methylcellulose and Colloids 1010; (3) with silica fume, triethanolamine, potassium aluminium sulphate and sodium sulphate; (4) with all ingredients in 2 and 3

	Flexural strength (MPa)		
Concrete	28 days	14 days	7 days
1	5.00 (±5%)	4.22 (±4%)	3.10 (±4%)
2	7.95 (±6%)	6.65 (±3%)	4.84 (±2%)
3	7.86 (±3%)	5.89 (±2%)	5.03 (±4%)
4	9.23 (±9%)	7.74 (±9%)	5.90 (±7%)

Table 4 Flexural toughness of concrete at different curing ages. (1), (2), (3) and (4) are as defined in *Table 3*

	Flexural toughness (MPa cm)		
Concrete	28 days	14 days	7 days
1	0.083 (±5%)	0.077 (±4%)	0.047 (±4%)
2	0.221 (±6%)	0.210 (±3%)	0.123 (±2%)
3	0.187 (±3%)	0.095 (±2%)	0.107 (±4%)
4	0.253 (±9%)	0.198 (±9%)	0.085 (±7%)

Table 5 Compressive strength of concretes at different curing ages. (1), (2), (3) and (4) are concrete types as defined in *Table 3*

	Compressive strength (MPa)		
Concrete	90 days	28 days	7 days
1	30.35 (±3%)	29.20 (±2%)	27.23 (±4%)
2	25.48 (±6%)	24.71 (±5%)	23.39 (±9%)
3	56.67 (±5%)	52.56 (±3%)	35.09 (±3%)
4	36.90 (±8%)	35.69 (±7%)	26.90 (±8%)

Table 6 Air content of concretes. (1), (2), (3) and (4) are concrete types as defined in *Table* 3

Concrete	Air content (%)
1	1
2	7
3	3
4	6

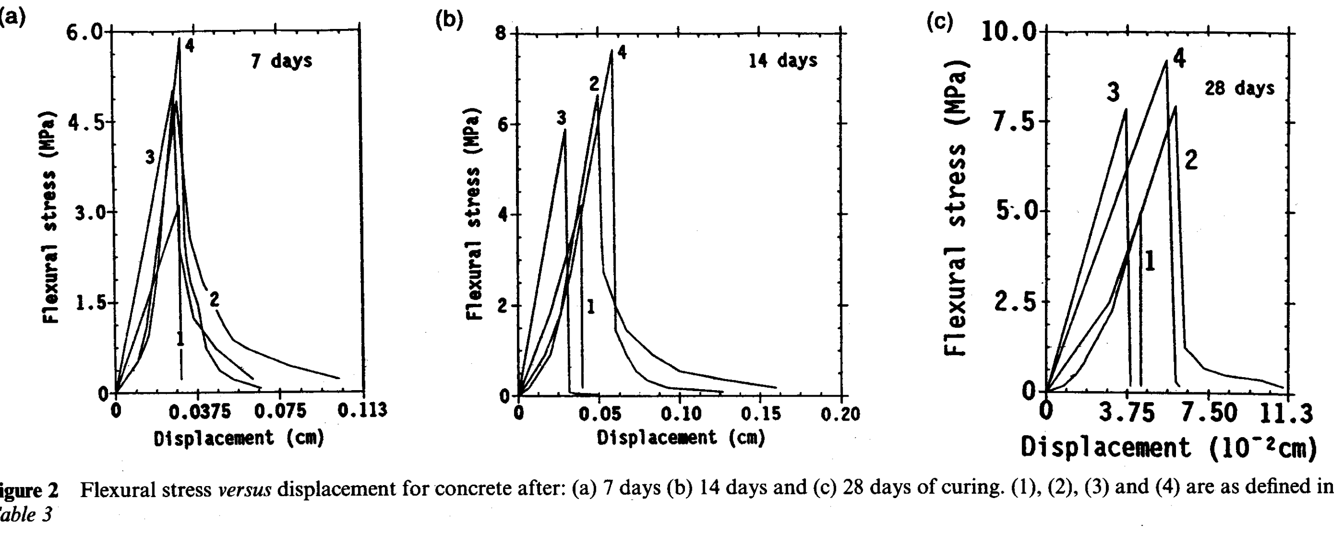

Figure 2 Flexural stress *versus* displacement for concrete after: (a) 7 days (b) 14 days and (c) 28 days of curing. (1), (2), (3) and (4) are as defined in *Table 3*

strength at different curing ages for each mix. From this table, one can see that the addition of fibers decreases the compressive strength, whereas the addition of silica fume increases the compressive strength. When both fibers and silica fume are present (type 4), the compressive strength at 28 and 90 days are higher than that of plain concrete.

Air content

The air content was measured using ASTM C231-82. *Table 6* shows the air content. Comparison of rows 1 and 2 and of rows 3 and 4 shows that the use of fibers significantly increases the air content.

Freeze–thaw durability

Table 7 gives the freeze–thaw durability test (ASTM C666) results. Freeze–thaw cycling started after 14 days of curing. Thirty cycles (30 days) were conducted for each specimen. After that, the flexural strength was measured and compared with that of the same kind of concrete that had not undergone cycling (just 14 + 30 = 44 days of curing). For concrete 1 (as defined in *Table 3*), cycling decreases the flexural strength by 12%. For concrete 2 (as defined in *Table 3*), cycling decreases the flexural strength by 6.9%. For concrete 3 (as defined in *Table 3*), cycling decreases the flexural strength by 10%. For concrete 4, cycling decreases the flexural strength by 5.1%. Comparison of concrete 1 with concrete 2 and of concrete 3 with concrete 4 shows that the addition of fibers improves the freeze–thaw durability. The combined use of fibers and silica fume gives the highest freeze–thaw durability.

Table 7 Freeze–thaw durability testing of concretes. (1), (2), (3) and (4) are concrete types as defined in *Table 3*

	Flexural strength (MPa)		
Concrete	44 days	14 days, then 30 cycles at 1 cycle per day	Freeze–thaw durability* (%)
1	5.3 (±2%)	4.7 (±2%)	88
2	8.1 (±7%)	7.5 (±6%)	93
3	8.1 (±4%)	7.3 (±5%)	90
4	9.7 (±8%)	9.2 (±9%)	95

* Fractional retention of flexural strength after thermal cycling

Chemical attack resistance

Table 8 gives the results of changes in compressive strength after 28 days of curing in water and then 182 days of exposure to 3% NaCl or 5% Na_2SO_4 solution for the four different concrete mixes (as defined in *Table 3*). Concretes with chemical agents and silica fume, whether containing fibers or not (concretes 3 and 4), are more chemically resistant than concretes without chemical agents or silica fume (concretes 1 and 2). Comparison between concretes 1 and 2 and between concretes 3 and 4 show that the addition of fibers decreases the chemical resistance slightly.

Figures 3 and *4* give the fractional weight loss after 28 days of curing in water and subsequently different times of immersion in 3% NaCl and 5% Na_2SO_4 solutions, respectively. Both figures show that the addition of

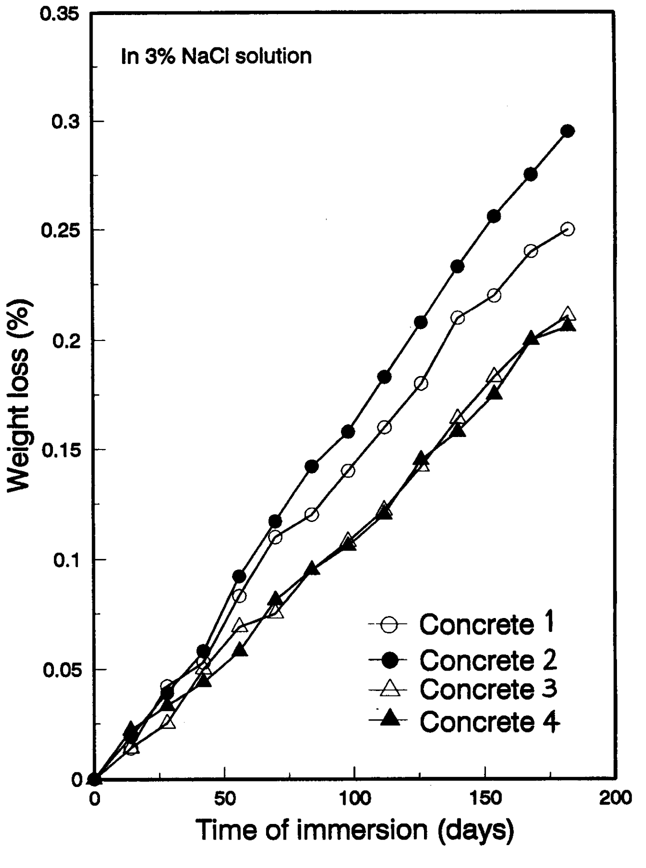

Figure 3 Fractional weight loss *versus* time of immersion in 3% NaCl solution. (1), (2), (3) and (4) are defined as in *Table 3*

Table 8 Chemical attack resistance of concretes. (1), (2), (3) and (4) are concrete types as defined in *Table 3*

	Compressive strength (MPa)			Fractional weight decrease after chemical attack	
Concrete	After 28 days in water and 182 days in air	After 28 days in water and 182 days in 3% NaCl solution	After 28 days in water and 182 days in 5% Na_2SO_4 solution	In 3% NaCl solution	In 5% Na_2SO_4 solution
1	30 (±8%)	29 (±4%)	28 (±8%)	6.3%	7.7%
2	25 (±10%)	23 (±2%)	23 (±9%)	7.4%	7.9%
3	54 (±5%)	53 (±6%)	52 (±6%)	2.6%	3.5%
4	38 (±4%)	36 (±6%)	36 (±2%)	4.6%	4.6%

chemical agents and silica fume helps to reduce chemical attack, whether fibers are present or not. *Figures 3* and *4* provide trends that are consistent with the change of compressive strength presented in *Table 8*. Results shown in *Table 8*, *Figures 3* and *4* also indicate that the rate of degradation in the 3% NaCl solution is less than that in the 5% Na_2SO_4 solution for concretes 1, 2 and 3 (as defined in *Table 3*), though the two rates are the same for concrete 4. No appreciable surface degradation was observed in any of the test specimens exposed to either of the chemical solutions. The fractional weight loss for all specimens was small, though the decrease in compressive strength was more significant. Thus, even without surface degradation, the compressive strength was decreased when concrete was exposed to a severe chemical environment.

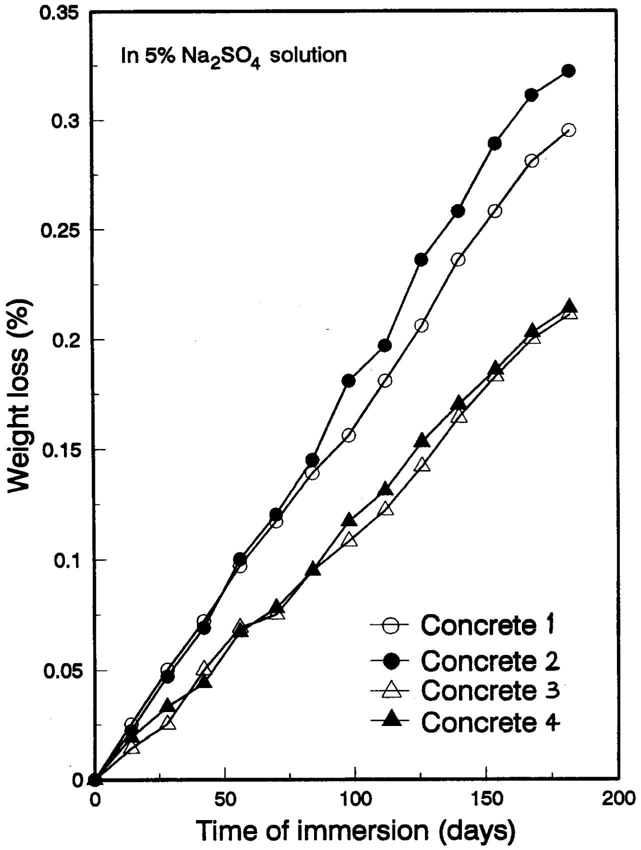

Figure 4 Fractional weight loss *versus* time of immersion in 5% Na_2SO_4 solution. (1), (2), (3) and (4) are as defined in *Table 3*

Table 9 Electrical resistivity of concretes. (1), (2), (3) and (4) are concrete types as defined in *Table 3*

Concrete	Electrical resistivity (Ω.cm)
1	1.36×10^7
2	3.70×10^6
3	1.19×10^7
4	2.32×10^6

Electrical resistivity

The electrical resistivity was measured by the four-probe method (two outer probes for passing current and two inner probes for measuring the voltage), using silver paint for electrical contacts. The silver paint was applied around the whole perimeter of the rectangular sample in four planes perpendicular to the current direction, which was along the longest dimension of the sample. *Table 9* shows the resistivity (at 14 days of curing). The fibers greatly decreased the electrical resistivity, while the silica fume slightly decreased the resistivity. The extent of decrease of the resistivity by the fiber addition provides an indication of the degree of fiber dispersion[12].

DISCUSSION

The dominating effects of the fibers (as opposed to silica fume) in decreasing the drying shrinkage strain and in increasing the flexural toughness of the concretes support the occurrence of fiber bridging. In spite of the low fiber volume fraction (0.19%), the fibers significantly decrease the drying shrinkage strain, increase the flexural toughness, increase the flexural strength and decrease the electrical resistivity, suggesting that the fibers are well dispersed. The fact that the fibers decrease the compressive strength, increase the freeze–thaw durability and decrease the chemical attack resistance is attributed to the increase in air content.

Comparison of concretes 1, 2, 3 and 4 shows that, for the lowest drying shrinkage, highest flexural strength and toughness, good compressive strength, highest freeze–thaw durability and good chemical attack resistance, the use of both fibers and silica fume (i.e. concrete 4 of *Table 3*) is recommended. The material cost of concrete type 4 is 39% higher than that of concrete type 1 (plain concrete).

Reference 3 reported drying shrinkage strains of 2.5×10^{-4}, 1.3×10^{-4}, 1.2×10^{-4} and 6×10^{-5} at 14 days for cements (without aggregate) with 3 mm long carbon fibers at 0, 1, 3 and 5% by volume respectively. The difference from our results is not only due to the lower fiber content (0.2 vol.%) of this work, but is also due to the presence of aggregates in this work and the absence of aggregates in ref. 3. Not only does the aggregate's presence matter, the size of the aggregate matters. Drying shrinkage testing was also performed on carbon fiber reinforced mortars (with a fine aggregate but without a course aggregate) and it was found that the fractional decrease in the drying shrinkage strain due to the carbon fiber addition is much less in the absence of the coarse aggregate than in the presence of the coarse aggregate. Without the coarse aggregate, the combination of carbon fibers (0.24 vol.%) and silica fume decreases the drying shrinkage strain at 14 days of moist room curing by 15% (from 2.6×10^{-3} to 2.2×10^{-3})[13]; with the coarse aggregate, the combination of carbon fibers (0.19 vol.%) and silica fume decreases the drying shrinkage strain at 14 days of moist room curing by 84% (from 1.2×10^{-4} to 1.9×10^{-5}). In general, the presence of a coarse aggregate greatly decreases the drying shrinkage strain. With the relatively small drying shrinkage strain in the presence of a coarse aggregate, the carbon fiber addition causes a relatively large *fractional* decrease in the drying shrinkage strain. The effect of adding carbon fibers on the drying shrinkage strain of concrete is much larger than that of adding steel, polypropylene or cellulose fibers[5–7]; this difference is probably due to the higher degree of fiber dispersion and the smaller fiber diameter in the carbon fiber case. For example, the steel fiber diameter was 400 μm[5], compared to the carbon fiber diameter of 10 μm in the present study.

CONCLUSIONS

The use of 0.19 vol.% short carbon fibers (0.5% of the cement weight) and silica fume (0.15 of the cement weight) in concrete results in an 84% decrease of the drying shrinkage strain (i.e. a shrinkage strain of 1.9×10^{-5} at 14 days of curing), in addition to increases in the flexural toughness, flexural strength and freeze–thaw durability. The carbon fibers dominate the silica fume in lowering the drying shrinkage and increasing the flexural toughness. The origin of these effects of the fibers is fiber bridging. However, both fibers and silica fume contribute to lowering the drying shrinkage strain and increasing the flexural strength, toughness and freeze–thaw durability. On the other hand, the addition of fibers was shown to decrease the compressive strength and lower the chemical attack resistance (due to the increase in air content), while the silica fume increases the compressive strength and the chemical attack resistance. Thus the combined use of fibers and silica fume maintains good compressive strength and good chemical attack resistance.

REFERENCES

1 ACI 223-93 Standard Practice for the Use of Shrinkage-Compensating Concrete

2 Gruner, P.W. and Plain, G.A. Type K shrinkage-compensating cement in bridge deck concrete. *Concrete Int.* 1993, **15**, 44

3 Banthia, N. Carbon fiber cements: structure, performance, applications and research needs. ACI SP-142[1], *Fiber Reinforced Concrete*[1], Eds. J.I. Daniel and S.P. Shah, ACI, Detroit, 1994

4 Park, S.B., Lee, B.I. and Lim, Y.S. Experimental study on the engineering properties of carbon fiber reinforced cement composites. *Cement and Concrete Research* 1991, **21**, 589

5 Chern, J. and Young, C. Study of factors influencing drying shrinkage of steel fiber reinforced concrete. *ACI Materials J.* 1990, **87**, 123

6 Grzybowski, M. and Shah, S.P. Shrinkage cracking of fiber reinforced concrete. *ACI Materials J.* 1990, **87**, 138

7 Sarigaphuti, M., Shah, S.P. and Vinson, K.D. *ACI Materials J.* 1993, **90**, 309

8 Carette, G.G. and Malhotra, V.M. Mechanical properties, durability, and drying shrinkage of portland cement concrete incorporating silica fume. *Cement Concrete, and Aggregates* 1983, **5**, 3

9 Padron, I. and Zollo, R.F. Effect of synthetic fibers on volume stability and cracking of portland cement concrete and mortar. *ACI Materials J.* 1990, **87**, 327

10 Soroushian, P., Nagi, M. and Hsu J. Optimization of the use of lightweight aggregates in carbon fiber reinforced cement. *ACI Materials J.* 1992, **89**, 267

11 Soroushian P., Aouadi, F. and Nagi, M. Latex-modified carbon fiber reinforced mortar. *ACI Materials J.* 1991, **88**, 11

12 Chen, P., Fu. X. and Chung, D.D.L. Microstructural and Mechanical Effects of Latex, Methylcellulose and Silica Fume on Carbon Fiber Reinforced Cement. *ACI Mater. J.* in press

13 Chen, P. and Chung, D.D.L. Concrete reinforced with up to 0.2 vol.% of short carbon fibers. *Composites* 1993, **24**, 33