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CARBON FIBER REINFORCED CEMENT COMPOSITES IMPROVED BY USING CHEMICAL AGENTS

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ABSTRACT

By using short pitch-based carbon fibers (0.5% by weight of cement, 0.28 vol.% of cement mortar, or 4.5 Kg fibers/m^3 cement mortar), together with a water reducing agent and an accelerating admixture, the compressive, tensile and flexural strengths of the carbon fiber reinforced cement mortar were found to increase by about 18-31%, 113-164% and 89-112%, respectively, compared to the corresponding plain cement values. The ductility was also much improved. In addition, the electrical resistivity decreased to 0.1% of the plain cement value. The optimum fiber length was 3.0 - 5.1 mm. By arranging unidirectional continuous carbon fibers (0.25% by weight of cement or 0.13 vol.% of cement mortar) near one side of a cement specimen, together with the use of a water reducing agent and an accelerating admixture, the flexural strength of the specimen increased by 170% compared to the plain cement value.

Introduction

The addition of short or continuous inorganic fibers (glass, asbestos, steel, carbon, etc.) increases the tensile and flexural strengths of cements [1,2]. However, asbestos fibers are carcinogenic, steel fibers tend to rust and glass fibers deteriorate in the highly alkaline environment of cement. Carbon fibers are inert, medically safe, as strong as steel fibers and more chemically stable than glass fibers in an alkaline environment. Moreover, carbon fibers are low in density, especially compared to steel fibers, their strength-to-density ratio is one of the highest among all fiber types. The main drawback of carbon fibers has been its high cost, and low cost is essential for most applications of cements. During the recent few years,

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short pitch-based carbon fibers have become common and their prices have steadily dropped, now down to about US $10/lb. This changed economic picture, together with the attractive properties of carbon fibers, motivated us to undertake a renewed investigation of carbon fiber reinforced cements.

In recent years the main development in the field of cements in general has been in the use of additives such as set-accelerating and early strength-enhancing agents and water-reducing agents [3]. Such chemical agents also impart higher compressive strength to the cement. An example of an accelerating admixture is 0.01-12 wt.% alkali metal or alkaline earth nitrite (i.e., $Ca(NO_2)_2$, 0.01-6 wt.% alkali metal or alkaline earth bromide (i.e., KBr), 0.003-3 wt.% (all based on cement) triethanolamine, together with 15-25 wt.% pozzolan (i.e. fly ash) [4]. Examples of water-reducing agents are Na lignosulfonate [5] and polyalkylaryl sulfonate [6]. Although accelerating admixtures have been applied to cements without fiber reinforcements, they have not previously been applied to cements with carbon fiber reinforcements. In this work, by using chemical agents in short carbon fiber reinforced cements, we have succeeded in doubling the tensile and flexural strengths with only 0.3 vol.% (0.5% by weight of cement) short carbon fibers whereas previous workers (without using chemical agents) required 4 vol. % short carbon fibers in order to double these strengths [7]. Because of the relatively high cost of carbon fibers, this means much cost savings in the use of the improved carbon fiber reinforced cements of this work.

For short random fibers dispersed uniformly in a matrix, the reinforcement effect is relatively low compared with that from aligned continuous fibers [8]. For example, it was reported that the same flexural strength was achieved with either 3 vol.% short fibers or 0.3-0.5 vol.% continuous fibers [9]. Therefore, even though continuous carbon fibers are more expensive than short carbon fibers, they are used for the reinforcement of cement products such as concrete lids, concrete pipes, etc. [10]. In this work, by using 0.13 vol.% (0.25% by weight of cement) continuous carbon fibers, together with chemical agents, we were able to increase the flexural strength by a factor of 2.7.

Carbon fibers have an additional advantage of having a high electrical conductivity. Since cement itself is a poor electrical conductor, the presence of carbon fibers greatly increases the electrical conductivity of the cement. The high electrical conductivity makes the cement useful as a material for anti-static flooring [11], the walling of electromagnetic shield rooms [12], etc. In this work, by using 0.3 vol.% (0.5% by weight of cement) short carbon fibers together with the accelerating admixture (which also serves to increase the electrical conductivity), we have succeeded to decrease the electrical resistivity of the cement by a factor of 5000, resulting in an electrical resistivity of only 6.7 ohm.cm.

The most commonly used carbon fiber length in previous works is 10 mm (0.39 in) [7,13,14]. However, it was reported that set cement properties were improved more using 3 mm carbon fibers rather than 10 mm fibers [6]. Furthermore, the molding properties of the cement were deteriorated by the addition of carbon fibers [15]. This situation prompted us to investigate systematically the dependence on carbon fiber length ranging from 3 mm to 50 mm. The optimum length for the best tensile and flexural strengths was thus found to range from 3 to 6 mm.

This paper is a systematic study of the effects of carbon fiber content,

carbon fiber length and chemical agents on the tensile, flexural and compressive properties as well as the electrical resistivity of the cement.

Raw materials

The cement powder used was Portland cement (Type I) produced by Lafarge Corporation. It is composed chiefly of $3CaO \cdot SiO_2$ (45.7 wt.%), $2CaO \cdot SiO_2$ (30.3 wt.%), $3CaO \cdot Al_2O_3$ (6.1 wt.%), $4CaO \cdot Al_2O_3 \cdot Fe_2O_3$ (9.2 wt.%), together with several minor oxides such as SO_3 (2.63 wt.%), MgO (3.38 wt.%), etc. The sand used was crystalline silica (quartz), middle grade.

Short carbon fibers were pitch-based and unsized. They were Carboflex chopped carbon fibers kindly provided by Ashland Petroleum Company. Five fiber lengths were used (3.0, 5.1, 12.7, 25.4, 50.8 mm). The fiber properties are shown in Table 1.

Table 1 Properties of short carbon fibers

Filament diameter	12 μm
Tensile strength	690 MPa
Tensile modulus	48 GPa
Elongation at break	1.6%
Electrical resistivity	30 μohm.m
Specific gravity	1.6
Carbon content	95% wt.

Continuous carbon fibers were pitch-based and sized. They were Amoco's Thornel P-25 X 2000-filament strands. Their properties are shown in Table 2.

The water reducing agent was TAMOL L Concentrate, which was a

Table 2 Properties of continuous carbon fibers

Filament diameter	11 μm
Tensile strength	1.40 GPa
Tensile modulus	1.60 GPa
Elongation at break	0.90%
Electrical resistivity	13 μohm.m
Specific gravity	1.90
Carbon content	97+ % wt.

concentrated aqueous solution (solids content 47.5 wt.%) of the sodium salt of a condensed naphthalene sulfonic acid, kindly provided by Rohm and Haas Co. It is a kind of anionic surfactant. The amount used was 1% by weight of cement.

The accelerating admixtures were of two kinds. Both kinds used triethanolamine (0.06% by weight of cement). In addition, admixture I used sodium sulfate (0.5 wt.%) and potassium aluminum sulfate (0.5 wt.%), whereas admixture II used sodium nitrite (0.5 wt.%) and sodium chloride (0.5 wt.%).

Unless otherwise stated, the sand/cement ratio is 0.5 by weight and the water/cement ratio is 0.36 by weight. (In some cases, the water/cement ratio was 0.27 by weight in order to maintain the mortar at almost the same flow value of about 130 $\pm$ 5 mm.)

Sample preparation and testing methods

According to ASTM C109-80, C190-82 (C150-58) and C348-80, specimens were prepared by using respectively a 2 in (5.1 cm) cubic mold for compressive testing, a briquet mold for tensile testing and a 1.57 by 1.57 by 6.30 in (4.0 by 4.0 by 16.0 cm) mold for flexural testing (under three-point bending). Specimens for electrical resistivity were prepared by using a 0.79 by 0.24 by 3.94 in (2.0 by 0.61 by 10.0 cm) mold.

The short carbon fibers were first mixed with the cement powder and sand. Then water and the chemical agents were put together and stirred with a mixer for 2 to 3 min. Then the mortar was poured into a mold. After 24 hr the specimens were demolded and left in an air-conditioned room at 20-22°C and 50-70% relative humidity. After curing for 1 to 28 days, they were tested.

The specimens were characterized mechanically using standard methods and a Material Testing System (MTS). For tensile tests, an MTS extensometer (Model 632.12B-20 Range) was used to measure the strain. At least three specimens of each combination of fiber length and content were tested for each type of mechanical measurement on the short fiber composites. The scatter in the data was $\pm$ 10%.

The four-probe method was used for measuring the electrical resistivity. Five data points were obtained per specimen. The scatter in the data was $\pm$ 15%.

Results

Dependence on carbon fiber content

Two different lengths of carbon fibers (3.0 and 5.1 mm) and no chemical agents were used in studying the dependence on the carbon fiber content, which ranged from 0.2 to 2.0% by weight of cement.

The compressive, tensile and flexural strengths after 7 days of curing are shown in Fig. 1-2 and Fig. 3-4 for 3.0 mm and 5.1 mm fibers respectively. The compressive strength slightly decreased as the carbon fiber content increased, whereas the tensile strength and the flexural strength increased with increasing fiber content. The increase of the tensile strength was up to 28% for 3.0 mm fibers and up to 41% for the 5.1 mm fibers. The increase of

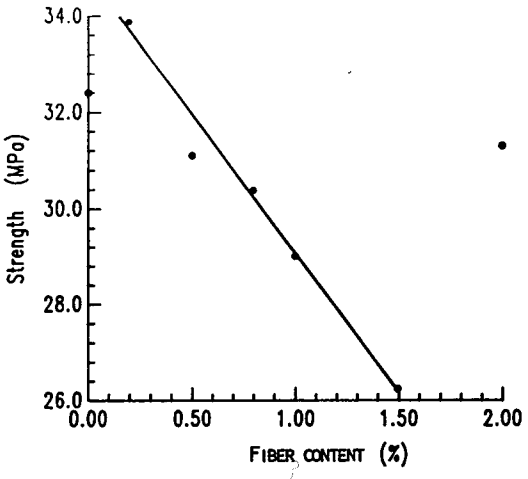

FIG. 1
Dependence of the compressive strength of carbon fiber (3.0 mm) reinforced cement on fiber content (% by weight of cement).

the flexural strength was up to 55% for the 3.0 mm fibers and up to 40% for the 5.1 mm fibers.

The dependence of the electrical resistivity on the carbon fiber content is shown in Fig. 5. The data were obtained after 2 days of curing for the 3.0 mm fibers and after 5 days of curing for the 5.1 mm fibers. [The dependence of the electrical resistivity on the curing age was very small, as long as the cement was set (Tables 3A and 3B)]. Most of the drop in electrical

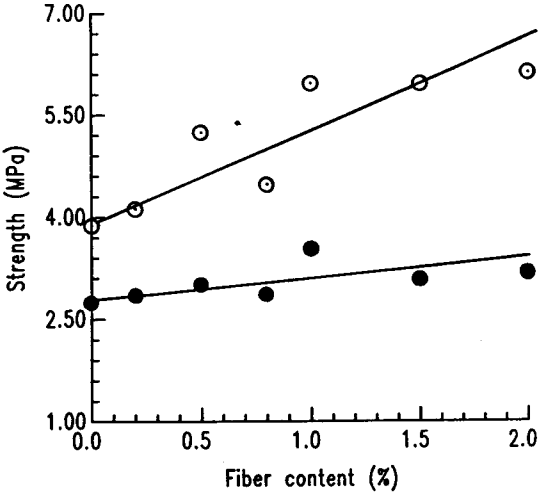

FIG. 2
Dependence of the tensile strength (solid circles) and flexural strength (open circles) of carbon fiber (3.0 mm) reinforced cement on fiber content (% by weight of cement).

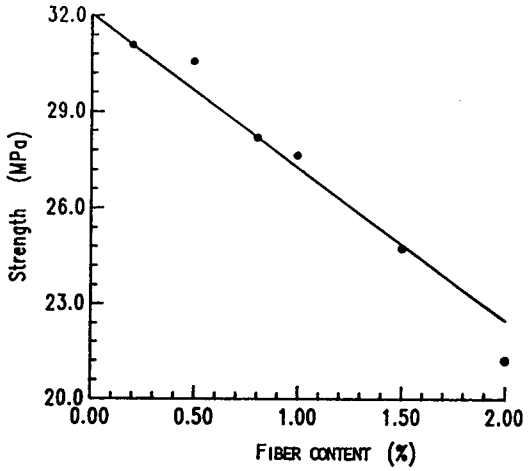

FIG. 3
Dependence of the compressive strength of carbon fiber (5.1 mm) reinforced cement on fiber content (% by weight of cement).

resistivity occurred for fiber contents of 0.5% or less. Increase of the fiber content beyond 1% had negligible effect on the electrical resistivity.

Examination of the data in Fig. 1-5 and the fact that carbon fibers are costly led us to conclude that a carbon fiber content of 0.5% was optimum. Hence this value of the fiber content was chosen for more detailed investigation.

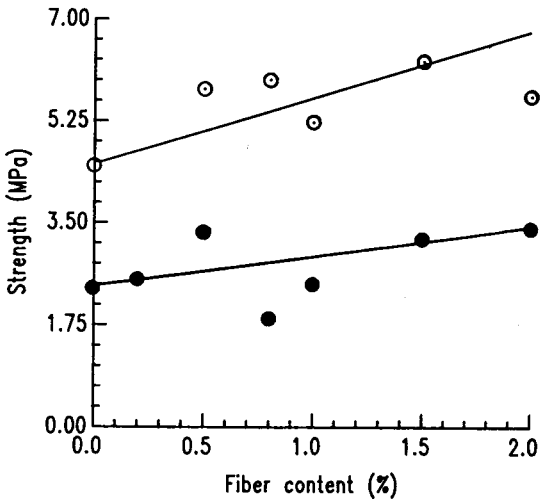

FIG. 4
Dependence of the tensile strength (solid circles) and flexural strength (open circles) of carbon fiber (5.1 mm) reinforced cement on fiber content (% by weight of cement).

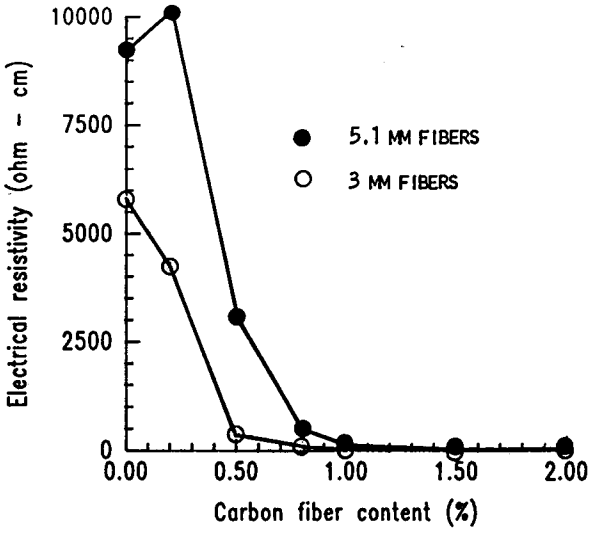

FIG. 5
Dependence of the electrical resistivity of carbon fiber reinforced cement on fiber content (% by weight of cement).

Table 3 Effect of curing age on the electrical resistivity in ohm.cm

A. For 3.0 mm carbon fibers

Curing age (days)	Fiber content (% by wt. of cement)					
	0.2	0.5	0.8	1.0	1.5	2.0
2	4260	355	92.3	29.5	22.2	17.5
5	5190	368	91.0	37.5	22.1	17.3
23	8730	378	93.7	37.9	22.3	17.2

B. For 0.5% fibers (by wt. of cement)

Curing age (days)	Fiber length (mm)			
	3.0	5.1	25.4	50.8
2	108	40.0	46.0	14.5
4	118	42.1	46.6	14.3
7	113	42.3	46.8	14.2

Dependence on carbon fiber length

For a fixed carbon fiber content of 0.5% (by weight of cement) and the absence of chemical agents, five different lengths of short carbon fibers were used to investigate the dependence on the fiber length. Table 4 shows the mechanical and electrical data obtained after 3 days of curing. The optimum lengths for most strengthening were 3.0 and 5.1 mm. The fact that the fibers of length 12.7 mm or above did not give as much strengthening as the shorter ones was due to the relative difficulty of dispersing the longer fibers. As shown in Table 4 and Fig. 6, the electrical resistivity decreased only slightly as the fiber length increased beyond 3.0 mm, even though the longer fibers, if well dispersed, should cause more fiber connectivity.

Effect of accelerating admixtures on cement without carbon fibers

Before considering the effect of both an accelerating admixture and carbon fibers on the cement, consider first the effect of an accelerating admixture alone on the cement. Table 5 gives the mechanical data obtained at

Table 4 Effect of carbon fiber length on strengths and electrical resistivity for 0.5% carbon fibers

Fiber length (mm)	0	3.0	5.1	12.7	25.4	50.8
Compressive strength (MPa)	26.7	25.0	27.0	24.5	25.0	23.9
Tensile strength (MPa)	2.03	2.66	2.63	2.17	2.45	2.18
Flexural strength (MPa)	3.88	5.16	5.76	5.28	4.84	3.88
Electrical resistivity (ohm.cm)	2870	118	/	42.1	46.6	14.3

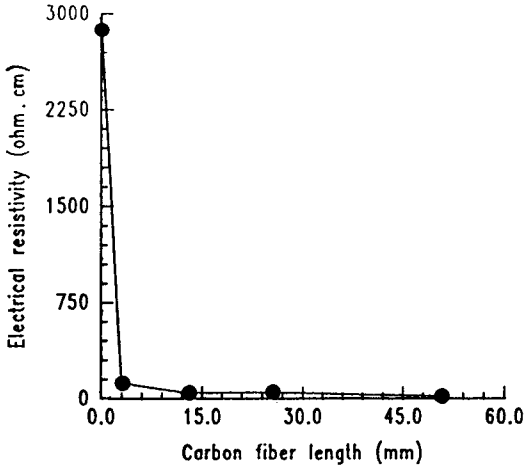

FIG. 6
Dependence of the electrical resistivity of carbon fiber reinforced cement on fiber length.

Table 5 Effect of accelerating admixture on strengths

		Strength (MPa)								
		Compressive			Tensile			Flexural		
Curing Time (days)		1	3	7	1	3	7	1	3	7
1	Plain cement	15.4	27.8	29.6	1.47	1.64	1.82	3.12	3.68	3.76
2	With accelerating admixture I	23.8	28.9	39.9	1.82	2.07	/	4.08	5.08	/
3	With accelerating admixture II	25.1	32.3	41	1.96	/	/	3.64	/	4.0

curing ages from 1 to 7 days for the plain cement, the cement with accelerating admixture I and the cement with accelerating admixture II. For a curing age of 1 day, accelerating admixture I caused a 55% increase in the compressive strength whereas accelerating admixture II caused a 63% increase in the compressive strength. The fractional increases in the tensile and flexural strengths were lower than those in the compressive strength. For example, accelerating admixture I caused the tensile strength at a curing age of 1 day to increase by 24%, while accelerating admixture II caused tensile strength at a curing age of 1 day to increase by 33%.

Effect of carbon fibers, accelerating admixtures and a water reducing agent on cement mortar

In carbon fiber reinforced cements, we used both an accelerating admixture and a water reducing agent. The water reducing agent served to improve the workability or fluidity of the cement mortar and to make the fibers disperse more evenly.

A fiber content of 0.5% (by weight of cement) and a fiber length of 5.1 mm were used. The amount of water reducing agent used was 1% (by weight of cement).

Table 6 gives the mechanical data obtained after 1-28 days of curing. For a curing age of 7 days, by using only carbon fibers (no water reducing agent or accelerating admixture) the tensile strength and flexural strength increased by 18 and 31%, respectively. For the same curing age of 7 days, using carbon fibers, a water reducing agent and accelerating admixture II, the compressive, tensile and flexural strengths increased by 18, 164 and 112%, respectively. Accelerating admixture I also caused much strengthening.

The strengthening due to the presence of an accelerating admixture is attributed to the improved bonding between the carbon fibers and the cement mortar. The improved bonding is revealed by the scanning electron microscope (SEM) photographs of Fig. 7(a) and 7(b), which are at the same magnification and were taken from the tensile fracture surfaces of a carbon fiber reinforced cement without any chemical agent and a carbon fiber reinforced cement with both a water reducing agent and accelerating admixture I, respectively. Fig. 7(a) shows carbon fibers with a relatively smooth surface, whereas Fig. 7(b)

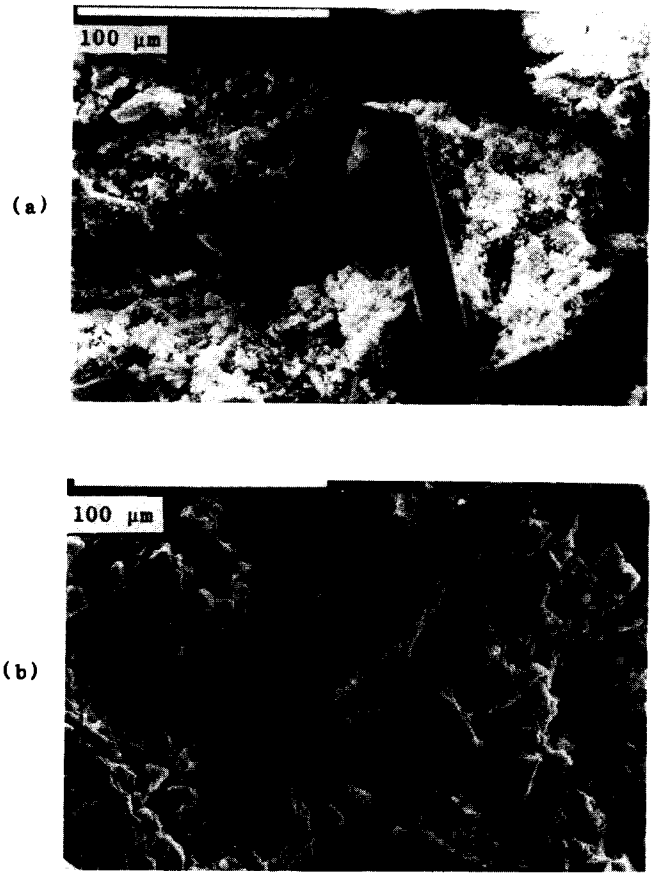

FIG. 7
SEM micrograph of the tensile fracture surface of carbon fiber reinforced cements
(a) without any chemical agent
(b) with a water reducing agent and accelerating admixture I.

shows carbon fibers with more adherends on their surface. In addition, the carbon fibers in Fig. 7(a) are much more severely pulled out than those in Fig. 7(b), as clearly shown in photographs taken at lower magnifications. There is much difference in the matrix also between Fig. 7(a) and (b), Fig. 7(b) shows the formation of more well developed and larger crystalline particles in the matrix.

Fig. 8 shows tensile stress-strain curves of (a) plain cement, (b) carbon fiber reinforced cement (0.5% fibers) with no chemical agent, (c) carbon fiber reinforced cement (0.5% fibers) with a water reducing agent and accelerating admixture I, and (d) carbon fiber reinforced cement (0.5% fibers) with a water reducing agent and accelerating admixture II. The ductility is clearly much increased by the carbon fibers and the chemical agents.

The electrical resistivity data obtained after 2 days of curing are shown in Table 7, together with the mechanical data obtained after 1 day of curing. Comparison of rows 1 and 2 of Table 7 shows that the addition of 0.5% carbon

Table 6 Effect of both carbon fibers and chemical agents on the strengths

	Strength (MPa)											
	Compressive				Tensile				Flexural			
Curing time (days)	1	3	7	28	1	3	7	28	1	3	7	28
1 Plain cement	14.9	27.8	29.6	/	1.47	1.64	2.23	/	3.12	3.68	3.76	8.36
2 With carbon fibers	15.8	26.1	29.8	/	2.28	2.17	2.64	3.50	4.24	5.16	4.92	9.76
3* With carbon fibers, water reducing agent and accelerating admixture I	28.8	35.8	38.9	/	3.10	5.03	4.76	5.43	5.36	6.48	7.12	10.24
4* With carbon fibers, water reducing agent and accelerating admixture II	22.8	38.3	35.0	/	3.43	5.11	5.88	/	6.88	7.60	7.96	/

*Water/cement ratio is 0.27

fibers (without chemical agents) to plain cement lowered the electrical resistivity to 3.1% of the plain cement value. Comparison of rows 1 and 3 shows that the addition of accelerating admixture I (without carbon fibers or water reducing agent) to plain cement lowered the electrical resistivity to 37% of the plain cement value, probably because of the electrolyte introduced by the accelerating admixture into the matrix, which contained some moisture.

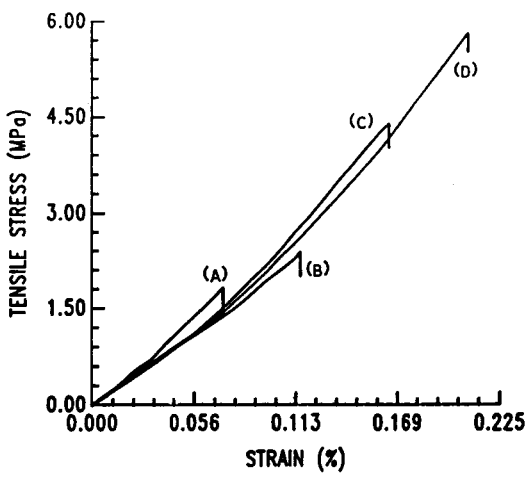

FIG. 8

Tensile stress-strain curve of
(A) plain cement
(B) carbon fiber reinforced cement (0.5% fibers) with no chemical agent,
(C) carbon fiber reinforced cement (0.5% fibers) with a water reducing agent and accelerating admixture I,
(D) carbon fiber reinforced cement (0.5% fibers) with a water reducing agent and accelerating admixture II.

Table 7 Effect of both carbon fibers and chemical agents on the electrical resistivity and strengths

		Electrical resistivity (ohm.cm)	Strength (MPa)		
			Compressive	Tensile	Flexural
1	Plain cement	35570	15.8	1.47	3.12
2	With carbon fibers	1115	15.8	2.03	4.00
3	With accelerating admixture I	13150	22.2	2.42	3.96
4	With carbon fibers and accelerating admixture I	6.7	21.5	2.66	4.76
5*	With carbon fibers, water reducing agent and accelerating admixture I	43.0	28.0	3.47	5.36

*Water/cement ratio is 0.27.

Comparison of rows 1 and 4 shows that the addition of carbon fibers and accelerating admixture I to plain cement lowered the electrical resistivity to 0.02% of the plain cement value. Comparison of rows 4 and 5 shows that the further addition of a water reducing agent raised the electrical resistivity slightly, probably because the water reducing agent introduced foam.

Table 7 also shows that the presence of carbon fibers, together with accelerating admixture I and a water reducing agent, gives the most strengthening -- about twice the strengths of plain cement.

Effect of continuous carbon fibers

Cements reinforced by unidirectional continuous carbon fibers were prepared by arranging a small amount of carbon fibers only near one side of a specimen with a hand lay-up method. The amount of carbon fibers ranged from 0.10 to 0.50% (by weight of cement).

In the sample preparation, cement mortar with a thickness of 1-2 mm was placed in the bottom of a 1.57 by 1.57 by 6.30 in (4.0 by 4.0 by 16.0 cm) mold. Continuous unidirectional carbon fibers, which had been previously impregnated with cement mortar, were placed on the mortar in the mold. Finally the rest of the mortar was poured in the mold. The specimens were demolded after 1 day and then they were cured in an air-conditioned room at 20 $\pm$ 2°C and a relative humidity of 50-65%.

The flexural strength was measured after 7 days of curing. The results are shown in Table 8 and Fig. 9. At the same carbon fiber content, the flexural strength was higher when the water reducing agent and accelerating admixture I were used. Comparison of rows 4 and 6 of Table 8 shows that the flexural strength of the specimen with 0.25% fibers and chemical agents was almost the same as that of the specimen with 0.5% fibers and no chemical

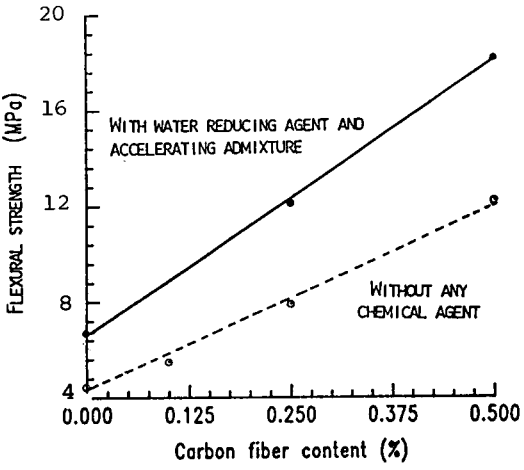

FIG. 9
Dependence of the flexural strength of continuous carbon fiber reinforced cement on fiber content (% by weight of cement).
Solid circles: with water reducing agent and accelerating admixture I.
Open circles: without any chemical agent.

agents. Comparison of rows 1 and 7 shows that the strengthening reached a factor of 4 when carbon fibers (0.5%), the water reducing agent and the accelerating admixture I were used. Fig. 10 shows the relation between the flexural strength and deflection for the specimens corresponding to rows 1,2,3,4 and 6 of Table 8. The deflection is taken as the amount of crosshead

Table 8 Effect of continuous carbon fibers on the flexural strength

		Fiber content (%)	Flexural strength (MPa)
1	Plain cement	0	4.48
2	With carbon fibers	0.10	5.52
3		0.25	7.92
4		0.50	12.24
5*	With carbon fibers and water reducing agent and accelerating admixture I	0	6.72
6*		0.25	12.08
7*		0.50	18.20

*Water/cement ratio is 0.27.

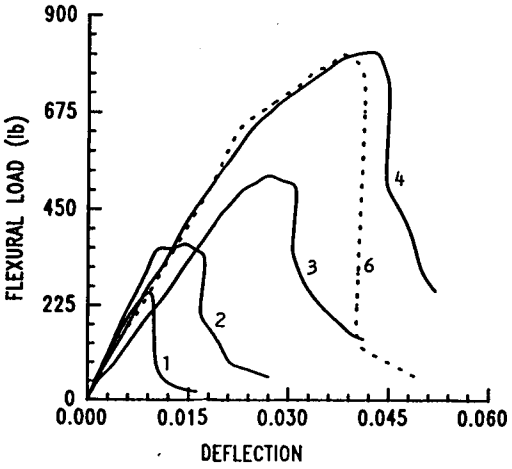

FIG. 10
Flexural load versus deflection during the flexural testing of samples corresponding to rows 1,2,3,4 and 6 of Table 8.

motion divided by the thickness (4.0 cm) of the specimen along the direction of crosshead motion.

Discussion

For carbon fiber reinforced cements, it is important to have good bonding between the carbon fibers and the cement matrix. For this purpose, organometallic-based coatings [16], latex coatings [17], anodic oxidation of carbon fibers [18], surface treatment with concentrated aqueous HNO_3 solution [19], surface treatment with chlorosulfonic acid to give hydrophilic carbon fibers [20] and introduction of phosphate groups [11] were used to enhance the bonding. Water reducing agents and silica fume were used to maintain good workability in the cement mortar and to make the fibers and the cement matrix contact each other firmly [6]. The above-mentioned methods, though effective, have their drawbacks. The coating and surface treatment of fibers are relatively cumbersome processes. Water reducing agents introduce foam and generate a higher dry shrinkage of the specimen.

In this work, accelerating admixtures were used because they make the cement particles disperse in water more easily, solutize the cement particles to form hydrolized calcium silicate gel, make the cement hydrate faster and generate crystalline compounds which fill the voids caused by the presence of the fibers. Therefore, by using an accelerating admixture, one enhances the strength of cement mortar, especially enhancing the early strength. The increase in strength of the cement mortar is accompanied by the increase in the bond strength between the fibers and the cement matrix.

Triethanolamine was chosen as an ingredient in both accelerating admixtures I and II because it is known to be a setting accelerator [21] and forms a complex with the hydrating silicate phase [21,22]. Accelerating admixture I also contains sodium sulfate [23,24] and potassium aluminum sulfate [25,26], accelerating admixture II also contains sodium nitrite [27] and sodium chloride [28]. Although these ingredients have separately been

used in cements previously and some of these ingredients have been used together in certain proportions previously, the accelerating admixtures I and II have not been previously used in cements in the proportions sited. Furthermore, this work provides the first use of any accelerating admixture in carbon-fiber reinforced cements.

A concentrated aqueous solution of the sodium salt of a condensed naphthalene sulfonic acid was chosen as the water reducing agent. Such a surfactant is known to adhere to reinforcing fibers, preventing the formation of fiber balls and allowing the fibers to be uniformly dispersed in the cement slurry [29].

We observed that the tensile strength and flexural strength increased quite linearly with increasing carbon fiber content. Such a dependence had been previously reported [8].

We observed that the compressive strength decreased quite linearly with increasing carbon fiber content. Such a dependence had also been previously reported [8].

Conclusions

(a) Low-cost pitch-based short carbon fibers effectively reinforce cement mortar, such that the compressive strength is slightly decreased with increasing carbon fiber content or with increasing carbon fiber length while the tensile and flexural strengths increased significantly with increasing fiber content or with increasing fiber length. For economy and performance, the optimum fiber content and length depend on parameters such as the properties of the carbon fibers, the types of mixer and cement, the water/cement ratio and the cement/sand ratio. In this work, a carbon content of 0.5% by weight of cement (i.e., 0.28 vol.% of cement mortar, or 4.5 Kg fibers/m^3 cement mortar) and a fiber length of 3 to 6 mm were found to be optimum.

(b) The addition of a water reducing agent and an accelerating admixture to cement mortar is very effective for improving the workability and the dispersion of carbon fibers and for enhancing the strength of the cement composite. In this work, the compressive, tensile and flexural strengths increased by about 18-31%, 113-164% and 89-112%, respectively for a curing age of 7 days. The ductility was also improved by using both carbon fibers and chemical agents.

(c) Using carbon fibers together with an accelerating admixture, the electrical resistivity of cement composites decreased to 0.02% of the plain cement value.

(d) For bending construction, by arranging unidirectional continuous carbon fibers near one side of a member, the effective factor of carbon fibers to enhance the flexural strength is higher than that of the case of randomly dispersed short carbon fibers. The use of 0.25% (by weight of cement) fibers, together with chemical agents, increased the flexural strength by 170%, the use of 0.50% fibers by weight of cement (or 0.26 vol.% of cement mortar), together with chemical agents, increased the flexural strength by 306%.

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SURFACE AND BULK PROPERTIES OF ANCIENT EGYPTIAN MORTARS, PART V: THERMAL STUDIES (b)

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ABSTRACT

The thermal properties of Ancient Egyptian mortars extracted from the Great Giza Pyramid, the second Giza Pyramid and the Sphinx temple were studied by simultaneous thermogravimetry, differential thermal analysis and differential thermogravimetry. Gypsiferous mortars containing calcite exhibit a number of endotherms in the ranges 20°-120°C, 120°C-190°C, 390°C-580°C and 585°C-890°C. The striking feature displayed by some of these mortars is the appearance of very sharp weight losses around 350°C and 400°C attributable to the formation of various soluble anhydrites. Such losses are in keeping with the unusual ageing effects detected previously (1) on these mortars by X-Ray Diffraction.

INTRODUCTION

In Part I of this series (1) Ancient Egyptian mortars extracted from the Great Giza Pyramid, the Second Giza pyramid and the Sphinx Temple were studied by X-Ray Diffraction. Such studies revealed in these mortars the presence of gypsum, calcite and silica. It was also shown that the γ-$CaSO_4$ modification displayed an unusually high stability, prevailing to a temperature as high as 400°C for a heating time extending to three hours.

The present study therefore addresses the need to understand the thermal behaviour of these mortars in an attempt to correlate these with the observed unusual ageing effects detected by X-Ray Diffraction.

MATERIALS AND METHODS

The present work deals with the 'MCON' samples described and reported in Part I of this series (1). These were extracted from the Great Giza Pyramid, the Second Giza Pyramid and the Sphinx Temple.