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Carbon Fiber Reinforced Concrete

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Abstract

The use of short pitch-based carbon fibers (0.05% of weight of cement, 0.189 vol. % concrete), together with a dispersant, chemical agents and silica fume, in concrete with fine and coarse aggregates resulted in a flexural strength increase of 85%, and a flexural toughness increase of 205%, a compressive strength increase of 22%, and a material price increase of 39%. The slump was 4 in at a water/cement ratio of 0/50. The air content was 6%, so the freeze-thaw durability was increased, even in the absence of an air entrainer. The aggregate size had little effect on the above properties. The minimum carbon fiber content was 0.1 vol. %. The optimum fiber length was such that the mean fiber length decreased from 12 mm before mixing to 7 mm after mixing, which used a Hobart mixer. The drying shrinkage was decreased by up to 90%. The electrical resistivity was decreased by up to 83%.

Executive Summary

The use of short pitch-based carbon fibers (0.5% of weight of cement, 0.189 vol. % of concrete), methylcellulose (a dispersant, 0.4% of weight of cement), Colloids 1010 (a defoamer, 0.13 vol. %), a water reducing agent (sodium salt of a condensed naphthalenesulfonic acid, 2% of weight of cement), triethanolamine (0.06% of weight of cement), potassium aluminum sulfate (0.5% of weight of cement), sodium sulfate (0.5% of weight of cement), and silica fume A (15% of weight of cement) in concrete with water/cement ratio 0.50 and cement: fine aggregate: coarse aggregate (#57, 100% passing through 1" sieve) ratio 1: 1.5 : 2.49 resulted in a flexural strength increase of 85% and a flexural toughness increase of 205% at 28 days of curing, a compressive strength increase of 22% at 90 days of curing, a slump of 4 in (compared to 6 in for plain concrete), and a material price increase of 39%. When an air entrainer was used with a water/cement ratio of 0.45, this formulation, compared to the corresponding plain air-entrained concrete, yielded a flexural strength increase of 79% and a flexural toughness increase of 53% at 28 days of curing.

This formulation resulted in an air content of 6% when an air entrainer was not used (compared to an air content of 1% for the corresponding plain concrete) and an air content of 9% when an air entrainer was used (compared to an air content of 6% for the corresponding plain air-entrained concrete). As a consequence of the increased air content the compressive strength was decreased by the fiber addition, though, in the presence of the chemical agents and microsilica, the compressive strength was increased by 22%. As another consequence, the freeze-thaw durability was increased, even in the absence of an air entrainer.

The aggregate size (from 100% passing 2 mm sieve to 100% passing 25 mm sieve) did not have a large effect on the effectiveness of the above mentioned formulation. However, the minimum carbon fiber content was 0.1 vol. %. The optimum fiber length was such that the mean fiber length decreased from 12 mm before mixing to 7 mm after mixing. The fiber length decrease occurred in the Hobart mixer stage of the mixing.

Dispersing the fibers in water with methylcellulose and Colloids 1010 gave similar results as dry mixing, but the former is more practical.

The drying shrinkage was decreased by the fiber addition by up to 90%.

The electrical resistivity was decreased by the fibers by up to 83%.

INTRODUCTION

As for brittle materials in general, concrete is strong under compression and weak under tension or flexure. This problem may be alleviated by the addition of short carbon fibers (typically ~ 10 μm in diameter) [1-6]. Almost all the previous work on carbon fiber reinforced concrete was conducted in Japan and it showed that the use of carbon fibers in the amount of 2 vol.% approximately doubled the flexural strength [1-4]. Recent work performed in U.S.A. by Zheng and Chung [6] showed the approximate doubling of the flexural strength with only 0.3 vol.% carbon fibers - an improvement resulting from the use of chemical agents.

All previous work on short carbon fiber reinforced concrete used isotropic pitch-based carbon fibers, which are the least expensive form of commercially available carbon fibers. Their tensile strength and modulus are much lower than those of continuous pitch-based or PAN-based carbon fibers that are used for aircrafts. The price of short pitch-based carbon fibers has been steadily decreasing. In the U.S., the price was $12/lb in 1985, $9/lb in 1990, and is expected to drop to below $5/lb [7]. This price decrease is giving much impetus to the use of carbon fibers in concrete. Nevertheless, it is desirable for economic reasons to keep the amount of carbon fibers in concrete to a minimum. Therefore, this paper is focused on concrete containing carbon fibers in the amount of ~ 0.2 vol.%, i.e. an extension of the work of Zheng and Chung [6].

Almost all of the previous work in both Japan and U.S.A. on carbon fiber reinforced concrete used only fine aggregate [1,2,4-6], so that the material was really mortar rather than concrete. Table 1 compares the results of various workers on pitch-based carbon fiber reinforced mortars. All previous workers used fibers in the amount of ≥ 1 vol. %, but this work used fibers in the amount of only 0.2 vol. %. In spite of the low carbon fiber content of this work, the resulting effect on the flexural strength is at least as good as in the previous work. Table 2 compares the results of various workers on pitch-based carbon fiber reinforced concretes. Akihama et al. [3] used microballoons as the aggregate, so the resulting concrete is not directly comparable to conventional concrete. Therefore, an objective of this paper is to extend the technology of carbon fiber reinforced concrete to concrete of common mix proportions. This extension deserves investigation, as the length of the carbon fibers relative to the aggregate size decreases as the aggregate size increases, so that the effectiveness of the carbon fibers in improving the flexural strength of concrete may decrease as the aggregate size increases. In this paper, we found that this aggregate size effect is quite minor, so that the technology of carbon fiber reinforced concrete is indeed viable for concrete with coarse aggregates, such as concrete that is typically used for highway pavements.

The technique of dispersing carbon fibers randomly in the concrete mix is critical to the success of the carbon fiber reinforced concrete technology. Two options are possible. One is to mix the fibers with cement and fine aggregate in the dry state (referred to as "Dry Mix" in this paper). The other option is to first disperse the fibers in water and then pour the dispersion into the slurry with cement and fine aggregate (referred to as "Wet Mix" in this paper). The second option is much more practical. Almost all published papers [1-5] on short carbon fiber reinforced concrete did not reveal the method of dispersing the carbon fibers. Zheng and Chung [6] did and they used Dry Mix. An objective of this paper is to develop a practical and effective method for dispersing the fibers and to compare the effect of Dry Mix and Wet Mix. We found that Wet Mix is an effective method only if a dispersant (methylcellulose in this work) and a defoamer (Colloids 1010 in this work) are used.

The freeze-thaw durability of carbon fiber reinforced concrete has not been previously studied. We found that carbon fibers increase the freeze-thaw durability of concrete.

EXPERIMENTAL

Raw materials

The short carbon fibers were pitch-based and unsized. Various nominal fiber lengths (provided by the fiber manufacturer) from 3.0 to 12.7 mm were used. Unless stated otherwise, fibers of nominal length 5.1 mm were used. The fiber properties are shown in Table 3.

Table 4 lists the aggregates used; Fig. 1 shows the particle size analysis of each aggregate. Table 5 describes the two types of mortars and two types of concrete used. Because

Aggregate D is most commonly used for highway pavements, Concrete D was given most attention in this work. Table 6 describes the various raw materials used. Unless stated otherwise, carbon fibers in the amount of 0.5% of the weight of the cement were used.

Mixing procedures

Two mixing procedures were used. They are referred to as "Dry Mix" and "Wet Mix", as described in Tables 7 and 8. Both procedures were used for Concrete D for the sake of comparison. Only Dry Mix was used for Mortar B. Only Wet Mix was used for Mortar A and Concrete C. For both procedures, a Hobart mixer with a flat beater as well as a stone concrete mixer were used. The Hobart mixer was necessary for mixing the fibers.

After pouring the mix into oiled molds, a vibrator was used to decrease the amount of air bubbles.

Fig. 2 shows the effect of Wet Mix (involving a Hobart mixer and then a stone concrete mixer) on the length distribution of the carbon fibers in Concrete D, as obtained by separately measuring the lengths of 200 fibers before and after Wet Mix. Mixing decreased the mean fiber length from 12 to 7 mm. Similar measurement done after the Hobart mixer stage and before the stone concrete mixer stage of Wet Mix showed a fiber length distribution essentially the same as Fig. 2(b). Thus, most of the fiber damage occurred during the Hobart mixer stage of Wet Mix.

Curing procedure

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

Mechanical testing

Flexural testing was performed on all specimens by three-point bending (ASTM C348-80), with a span of 9 in. The specimen size was 4x4x16 cm for mortars and was 3x3x11 in for concretes. For compressive testing the specimen size was 2x2x2 in (ASTM C109-80) for Mortar B and 4 in diameter x 8 in length (ASTM C39-83b) for Concrete D. Six specimens of each type of specimen were used for each type of test. 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.

<u>Mortar B</u>

The raw materials for Mortar B are listed in Table 9.

Table 10 shows the effect of carbon fibers and chemical agents on the flexural strength and compressive strength after 7, 14 and 28 days of curing. The use of both fibers (3.0 mm long), and chemical agents increased the flexural strength by 37%, 33% and 21% respectively after 7, 14 and 28 days, and increased the compressive strength by 40%, 22% and 17% respectively after 7, 14 and 28 days, as shown by comparing rows (1) and (4).The chemical agents alone are more effective than the fibers alone in increasing the flexural or compressive strength, as shown by comparing rows (2) and (3). Nevertheless, it is significant that the fibers increased the compressive strength as well as the flexural strength of the mortar, as shown by comparing rows (1) and (3). The effect of the fibers on the flexural and compressive strengths of the mortar containing chemical agents was small, as shown by comparing rows (2) and (4).

Table 11 shows the effect of carbon fiber length on the flexural and compressive strengths at 14 days of curing. The flexural strength increased monotonically with increasing nominal fiber length, but the difference in flexural strength between fiber lengths of 5.1 and 12.7 mm was small. The compressive strength was highest for an intermediate fiber length of 5.1 mm when no chemical agents were used; it decreased monotonically with increasing fiber length when chemical agents were used. Thus, for high flexural and compressive strengths, the optimum fiber length is 5.1 mm.

Table 12 shows the effect of carbon fiber content (3.0 mm long fibers) on the flexural and compressive strengths at 14 days of curing. The flexural strength increased monotonically with increasing fiber content, though the difference in flexural strength between fiber contents of 1.0% and 2.0% (of the weight of the cement) is small. The compressive strength was highest for the intermediate fiber content of 1.0% of the weight of the cement. Thus for economy and high strengths, the optimum fiber content is 1.0% of the weight of the cement.

The effect of each accelerating agent and various combinations of accelerating agents on the fluidity of the mortar mix was investigated by performing the slump test, and measuring the flexural strength after 3 days of curing. it was found that sodium sulfate (with or without other accelerating agents) decreased the slump. Table 13 shows the effect of the sodium sulfate content on the slump and flexural strength. The slump decreased with increasing sodium sulfate content, such that the slump decreased abruptly between sodium sulfate contents of 0.3 or 0.4% of the weight of the cement. The flexural strength increased with increasing sodium sulfate content from 0.2 to 0.5% of the weight of the cement. Thus, for good fluidity and high flexural strength, the optimum sodium sulfate content is 0.3% of the weight of the cement.

Concrete D with low fluidity

The raw materials for Concrete D are listed in Table 14. Dry Mix was applied when methylcellulose and Colloids 1010 were not used, and Wet Mix was applied when methylcellulose and Colloids 1010 were used, unless stated otherwise. This formulation resulted in a mix with low fluidity compared to another one (to be described in a following section) involving Wet Mix only. Concrete D of Table 14 is referred to as "Concrete D with low fluidity", whereas Concrete D involving Wet Mix only (to be described in a following section), is referred to as "Concrete D with normal fluidity". Note from Table 14 that the sodium sulfate content was the optimum amount of 0.3% of the weight of the cement.

Table 15 shows the effect of chemical agents and silica fume B on the flexural strength. Note that Table 15 involves no fibers. The use of both chemical agents and silica fume B increased the flexural strength by 68%, 49% and 58% respectively for 7, 14 and 28 days of curing, as shown by comparing rows (1) and (4) of Table 15. Silica fume B alone was more effective than chemical agents in increasing the flexural strength at 14 days, but was comparable to the chemical agents in the effect on the flexural strength at 7 and 28 days.

Table 16 shows the effect of carbon fibers, methylcellulose and Colloids 1010 on the flexural strength. Comparison between rows (1) and (2) of Table 16 shows that, for identical formulations, Dry Mix gave slightly higher flexural strength than Wet Mix. Comparison between rows (2) and (3) shows that, for Wet Mix, with fibers and chemical agents, methylcellulose increased the flexural strength. Comparison between rows (3) and (4) shows that, for Wet Mix with fibers, chemical agents and methylcellulose, silica fume B increased the flexural strength. Comparison between rows (3) and (5) shows that, for Wet Mix with fibers, chemical agents and methylcellulose, Colloids 1010 increased the flexural strength. Comparison between rows (4) and (5) shows that Colloids 1010 was more effective than silica fume B in increasing the flexural strength. Comparison between rows (1) and (5) shows that Wet Mix gave higher flexural strength than Dry Mix if both methylcellulose and Colloids 1010 were used. Row (5) of Table 16 corresponds to the formulation for the highest flexural strength for Concrete D of low fluidity. Comparison of row (5) of Table 16 with row (1) of Table 15 shows that the use of fibers, chemical agents, methylcellulose and Colloids 1010 increased the flexural strength by 105% and 79% respectively for 7 and 14 days of curing.

Table 17 gives the freeze-thaw durability test (ASTM C666) result. Temperature cycling was carried out between -40 and 10^oC, with a temperature accuracy of $\pm 3^oC$, at a rate of 1 cycle/day. Cycling started after 7 days of curing. Thirty cycles (30 days) were conducted. After that, the flexural strength was measured and compared to the same kind of concrete that had undergone no cycling (just 7 + 30 = 37 days of curing). For plain Concrete D, the cycling decreased the flexural strength by 27%. For Concrete D containing fibers, methylcellulose, chemical agents and silica fume B, the cycling decreased the flexural strength by 15%.

Mortar A

Table 18 shows the effect ofsilica fume A vs. silica fume B on the flexural strength at 3 days of curing. Comparison between rows (1) and (3) and comparison between rows (2) and (4) show that fibers and methylcellulose are effective in increasing the flexural strength. Comparison between rows (1) and (2) and comparison between rows (3) and (4) show that silica fume A gave higher flexural strength than silica fume B. Table 19 lists the properties of silica fume A and silica fume B. The lower SiO_2 content in silica fume B compared to silica fume A leads to less pozzalanic reaction with silica fume B, so that silica fume B gave lower flexural strength than silica fume A. In addition, the higher surface area of silica fume A contributed to the higher flexural strength.

Table 20 lists the raw matrials for Mortar A in the following investigation. Note that silica fume A rather than silica fume B was used. By "dispersant" (or "Dis"), we mean methylcellulose plus Colloids 1010.

Table 21 gives the effect of fibers, Dis, Chem and microsilica on the flexural strength of Mortar A. The use of fibers + Dis + Chem + silica fume A increased the flexural strength by 130% and 110% respectively after 7 and 14 days of curing. The effectiveness of fibers + Dis in increasing the flexural strength is comparable to or higher than that of Chem + silica fume A, as shown by comparing rows (2) and (3) of Table 21. The use of just fibers + Dis (without Chem or silica fume A) increased the flexural strength by 100% and 60% respectively after 7 and 14 days of curing, as shown by comparing rows (1) and (2).

Table 22 gives the effect of fibers, Dis, Chem and silica fume A on the flexural toughness of Mortar A. The use of fibers + Dis + Chem + silica fume A increased the flexural toughness by 130% and 380% respectively after 7 and 14 days of curing. The effectiveness of fibers + Dis in increasing the flexural toughness is higher than that of Chem + silica fume A for both 7 and 14 days of curing, as shown by comparing rows (2) and (3). The use of just fibers + Dis (without Chem or silica fume A) increased the flexural toughness by 190% and 430% respectively after 7 and 14 days of curing, as shown by comparing rows (1) and (2). The flexural toughness of Mortar A containing fibers + Dis is even higher than that of Mortar A containing fibers + Dis + Chem + silica fume A, as shown by comparing rows (2) and (4). Fig. 3 shows the plots of flexural stress vs. displacement during flexural testing of the four types of Mortar A (labeled (1), (2), (3) and (4) in Table 22 and Fig. 3) after 7 and 14 days of curing. These plots indicate that the high flexural toughness of (2) (i.e., Mortar A with fibers + Dis) is due to its high flexural strength and exceptionally high ductility.

Concrete D with normal fluidity

The raw materials for Concrete D with normal fluidity are listed in Table 23. Wet Mix was applied.

Comparison between Tables 23 and 14 shows that the water/cement ratio was higher for Concrete D with normal fluidity than for Concrete D with low fluidity. Moreover, the amount of water reducing agent was higher for Concrete D with normal fluidity than for Concrete D with low fluidity. In addition, the amount of methylcellulose was lower for Concrete D with normal fluidity than for Concrete D with low fluidity. Furthermore, the amount of sodium sulfate was higher for Concrete D with normal fluidity than for Concrete D with low fluidity.

Comparison between Tables 23 and 20 shows that the amounts of methylcellulose, water reducing agent and accelerating agents are the same for Concrete D with normal fluidity and Mortar A. The difference between the two sets of raw materials lies only in the water/cement ratio and in the aggregate, as required by the fact that Mortar A is a mortar whereas Concrete D is a concrete.

Table 24 shows the effect of fibers + Dis + Chem + silica fume A on the flexural strength of Concrete D with normal fluidity. The use of fibers + Dis + Chem + silica fume A increased the flexural strength by 90%, 83% and 85% respectively after 7, 14 and 28 days of curing, as shown by comparing rows (1) and (5). The effectiveness of just fibers + Dis in increasing the flexural strength is comparable to that of just Chem + silica fume A, as shown by comparing rows (2) and (3). The use of just fibers + Dis increased the flexural strength by 56%, 58% and 59% respectively after 7, 14 and 28 days of curing, as shown by comparing rows (1) and (2). Comparison between rows (2) and (4) shows that Chem is useful for increasing the flexural strength. Comparison between rows (4) and (5) shows that silica fume A is useful for increasing the flexural strength.

Table 25 shows the effect of fibers, Dis, Chem and silica fume A on the flexural toughness of Concrete D with normal fluidity. The use of fibers + Dis + Chem + silica fume A increased the flexural toughness by 80%, 160% and 205% respectively after 7, 14 and 28 days of curing, as shown by comparing rows (1) and (4). The effectiveness of just fibers + Dis in increasing the flexural toughness is superior to that of just Chem + silica fume A or that of fibers + Dis + Chem + silica fume A, as shown by comparing rows (2), (3) and (4). The use of just fibers + Dis increased the flexural toughness by 160%, 170% and 170% respectively after 7, 14 and 28 days of curing, as shown by comparing rows (1) and (2).

Fig. 4 shows the plots of flexural stress vs. displacement during flexural testing of the four types of Concrete D (labeled (1), (2), (3) and (4) in Table 25 and Fig. 4) after 7, 14 and 28 days of curing. These plots indicate that the high flexural toughness of (4) (i.e., Concrete D with fibers + Dis + Chem + silica fume A) after 14 days of curing is due to its high flexural strength as well as its high ductility. Comparison between (2), (3) and (4) at 28 days of curing shows that the relatively high flexural toughness of (2) is due to its high ductility.

Table 26 shows the compressive strength of Concrete D of normal fluidity. Comparison between Rows (1) and (4) of this table shows that the use of fibers + Dis + Chem + silica fume A gave a compressive strength that was quite close to that of plain concrete. However, comparison between Rows (3) and (4) shows that the use of just Chem + silica fume A gave much higher compressive strength than the use of fibers + Dis + Chem + silica fume A.

Fig. 5 shows the plot of compressive stress versus axial strain and that of compressive stress versus lateral strain for the samples corresponding to Rows (1) - (4) of Table 26 after 90 days of curing. Though (3) and (4) are comparably brittle in the axial direction, (4) is more ductile than (3) in the lateral direction.

Table 27 gives the freeze-thaw durability test (ASTM C666) result. Temperature cycling was carried out between -40 and 10^{o}C, with a temperature accuracy of $\pm$3^{o}C, at a rate of 1 cycle/day. Cycling started after 14 days of curing. Thirty cycles (30 days) were conducted. After that, the flexural strength was measured and compared to the same kind of concrete that had undergone no cycling (just 14 + 30 = 44 days of curing). For plain Concrete D, the cycling decreased the flexural strength by 12%. For Concrete D containing fibers + Dis, the cycling decreased the flexural strength by 6.9%. For Concrete D containing Chem + silica fume A, the cycling decreased the flexural strength by 10%. For Concrete D containing fibers + Dis + Chem + silica fume A, the cycling decreased the flexural strength by 5.1%. Hence, fibers + Dis are more effective than Chem + silica fume A in improving the freeze-thaw durability. Moreover, fibers + Dis + Chem + silica fume A are most effective in improving the freeze-thaw durability.

Air-entrained Concrete D with normal fluidity

Air-entrained Concrete D with normal fluidity used the same raw materials as in Table 23, except that water/cement = 0.45 (instead of 0.50) and air-entrainer/cement = 1% (instead of 0%). The air-entrainer used was Daravair (Table 6). The air content is given later in this paper. Tables 28 and 29 give the flexural strength and flexural toughness, respectively. Comparison of Rows (1) and (4) of Table 28 shows that the use of fibers + Dis + Chem + silica fume A increased the flexural strength of air-entrained Concrete D by 83%, 95% and 79% respectively after 7, 14 and 28 days of curing. Comparison of Rows (1) and (4) of Table 29 shows that the use of fibers + Dis + Chem + silica fume A increased the flexural toughness by 49%, 43% and 53% respectively after 7, 14 and 28 days of curing.

Fig. 6 shows the plots of flexural stress vs. displacement during flexural testing of the four types of air-entrained Concrete D (labeled (1), (2), (3) and (4) in Table 29 and Fig. 6) after 7, 14 and 28 days of curing. These plots indicate that the high flexural toughness of (4) (i.e., Concrete D with fibers + Dis + Chem + silica fume A) after 28 days of curing is due to its high flexural strength as well as its high ductility.

Comparison of Tables 29 and 25 shows that the use of fibers + Dis + Chem + silica fume A is much more effective for enhancing the flexural toughness of concrete without air-entrainment than concrete with air-entrainment. However, comparison of Tables 28 and 24 shows that the use of fibers + Dis + Chem + silica fume A is comparably effective for enhancing the flexural strength of concrete without air-entrainment and that with air-entrainment.

Concrete C

The raw materials for Concrete C were the same as those for Concrete D of normal fluidity (Table 23) except that Aggregate C was used instead of Aggregate D. Thus, comparison between Concrete C and Concrete D with normal fluidity provides a study of the effect of aggregate size.

Table 30 gives the effect of fibers, Dis, Chem and silica fume A on the flexural strength of Concrete C after 7 and 14 days of curing. The use of fibers + Dis + Chem + silica fume A increased the flexural strength by 100% and 73% respectively after curing for 7 and 14 days. The effect of just fibers + Dis on the flexural strength is comparable to that of just Chem + silica fume A. The use of just fibers + Dis increased the flexural strength by 49% and 54% respectively after 7 and 14 days of curing.

Table 31 gives the effect of fibers, Dis, Chem and silica fume A on the flexural toughness after 7 and 14 days of curing. The use of fibers + Dis + Chem + silica fume A increased the flexural toughness by 160% and 200% respectively after 7 and 14 days of curing. The effect of just fibers + Dis on the flexural toughness was comparable to or slightly larger than that of just Chem + silica fume A. The use of just fibers + Dis increased the flexural toughness by 100% after either 7 or 14 days of curing.

Slump and effect of the water/cement ratio

The water/cement ratio was 0.50 in Concrete D of normal fluidity. Keeping all other ingredients the same, we have varied the water/cement ratio from 0.50 to 0.40 and investigated the effect of this variation on the flexural strength and slump (ASTM C143-78). The decrease in the water/cement ratio increased the flexural strength but decreased the slump, as shown in Table 32 for Concrete D without air-entrainer. For case (4) with fibers + Chem + silica fume A, a decrease of the water/cement ratio from 0.50 to 0.45 decreased the slump from 4 to 1, so that a ratio of 0.50 is optimum.

For a water/cement ratio of 0.45, Table 32 also shows that the use of an air-entrainer increases the slump.

Air content

The air content was measured using ASTM C231-82. Table 33 shows the air content of Concrete D of normal fluidity without and with the air-entrainer. Comparison of Rows (1) and

(2) and of Rows (3) and (4) shows that the use of fibers significantly increased the air content. Even without the air-entrainer, the air content was 6% for Concrete D with fibers + Dis + Chem + silica fume A. With the air-entrainer, the air content was further increased.

Dry shrinkage

The dry shrinkage was investigated by measuring the length change of Mortar A and Concrete D of normal fluidity in accordance with ASTM C490-83a. The specimen size was 1 x 1 x 11.25 in for Mortar A and 3 x 3 x 11.25 in for Concrete D. The accuracy in the length change measurement was ± 0.0001 in. Fig. 7 shows the plots of drying shrinkage strain versus curing time for Mortar A curing in air and curing in water. For all samples, curing in water resulted in much less shrinkage than curing in air. However, for each case, the use of fibers decreased the shrinkage, irrespective of the presence of Chem + silica fume A. Fig. 8 shows the plot of drying shrinkage strain versus curing time for Concrete D curing in a moist room. The use of fibers + Dis + chem + silica fume A (case 4 in Fig. 8) lowered the drying shrinkage at 14 days by 90%, compared to that of plain concrete (case 1 in Fig. 8)

Volume fraction of fibers

The fiber content of 0.5% of the weight of the cement corresponds to the volume fractions shown in Table 34. Note that the volume fractions are all less than 0.25%. The volume fraction for Mortar B is particularly low.

Effectiveness of the fibers

The mix design for Mortar A, Concrete D with normal fluidity and Concrete C was all similar, as all involved Wet Mix, with Dis (methylcellulose + Colloids 1010). In contrast, Mortar B involved Dry Mix, without Dis. Therefore, comparison among Mortar A, Concrete C and Concrete D with normal fluidity provides a study of the effect of aggregate size. Both Concrete C and Concrete D contained 0.189 vol.% fibers, whereas Mortar A contained 0.244 vol.% fibers. Therefore, comparison between Concrete C and Concrete D is most appropriate for studying the effect of aggregate size.

Table 35 shows that the effect of aggregate size on the effectiveness of fibers + Dis + Chem + silica fume A for increasing the flexural strength and flexural toughness is not large. An increase in aggregate size (from that of Concrete C to that of Concrete D) did not degrade the effectiveness of fibers + Dis + Chem + silica fume A.

Table 36 shows that the effect of aggregate size on the effectiveness of fibers + Dis (without Chem or silica fume A) for increasing the flexural strength and flexural toughness is not large. An increase in aggregate size (from that of Concrete C to that of Concrete D) increased the effectiveness of fibers + Dis slightly.

The combination of Tables 35 and 36 shows that the fibers (5 mm long) are similarly effective for aggregate size ranging to 3/4" (19 mm, Aggregate C) and for aggregate size ranging to 1" (25 mm, Aggregate D), as well as for aggregate size ranging to 2 mm (Aggregate A), even though the aggregate size is smaller than the fiber length in the case of Aggregate A and is larger than the fiber length in the case of Aggregate C and Aggregate D.

Table 37 shows the effect of aggregate size on the effectiveness of fibers + Chem (Dry Mix) for increasing the flexural strength. Because of the difference in fiber volume fraction between Mortar B and Concrete D with low fluidity, the flexural strength increases cannot be directly compared with one another. Since the fiber volume fraction in Concrete D with low fluidity is about twice that in Mortar B, it can probably be concluded that the effect of aggregate size is small.

Comparison between Tables 36 and 37 shows that Mortar B is particularly poor in the effectiveness of the fibers in increasing the flexural strength. This is attributed to the particularly low volume fraction of fibers in Mortar B. Hence, the minimum fiber volume fraction for the fibers to be effective for increasing the flexural strength is around 0.10%.

Comparison between Tables 36 and 37 with regard to Concrete D shows that Wet Mix (with Dis) and Dry Mix (with Chem) gave comparable effectiveness of the fibers for increasing the flexural strength. For a more direct comparison between Wet Mix (with Chem), and Dry Mix (with Chem), refer to Table 16.

Electrical resistivity

The electrical resistivity was measured by the four-probe method, using silver paint for electrical contacts. Table 38 shows the resistivity of Concrete D with normal fluidity and Mortar A. The presence of fibers + M decreased the resistivity by 73% and 83% respectively for Concrete D and Mortar A. The presence of Chem + silica fume A (without fibers) decreased the resistivity by 13% and 35% respectively for Concrete D and Mortar A. The presence of fibers + M + Chem + silica fume A decreased the resistivity by 83% and 84% respectively for Concrete D and Mortar A. Hence, fibers + M are much more effective than Chem + silica fume A for decreasing the electrical resistivity.

Increasing the fiber content beyond 0.5% of the weight of the cement is expected to greatly increase the effectiveness of the fibers for decreasing the electrical resistivity.

Microscopy

Scanning electron microscopy (SEM) was performed on the fracture surfaces after flexural testing. It revealed some fiber pull-out, which furthermore showed that the individual fibers were quite uniformly distributed. No fiber clustering was observed. No fiber damage was observed.

PRICE

Table 39 shows the percentage material price increase per cubic yard of the various mortars and concretes due to the addition of various additives. The fibers are the most expensive type of additive, although the price increase due to fibers (0.5%) + M + 1010 is not much greater than that due to Chem + silica fumeA. The best concrete studied in this work corresponds to row (10) of Table 33 - a price increase of 39%.

The use of fibers in the amount of 1.0% of the weight of the cement was not investigated in this work, but it is expected to further increase the flexural strength and flexural toughness. The best such concrete corresponds to row (14) - a price increase of 56%.

The processing price increase is associated with the use of both a Hobart mixer and a stone concrete mixer.

COMPETITION

The concrete of best performance in this work is Concrete D (with normal fluidity) with fibers (0.5% of the weight of the cement) + Dis + Chem + silica fume A. Its properties (at 28 days of curing) and price relative to plain Concrete D are summarized in Table 40 in the column labeled Concrete 1.

The competitive concrete is Concrete D (with normal fluidity) with Chem + silica fume A (no fibers). Its properties (at 28 days of curing) and price relative to plain Concrete D are summarized in Table 40 in the column labeled Concrete 2. The properties and price of Concrete 1 relative to those of Concrete 2 are shown in Table 41.

Competitive fibers include organic and steel fibers. Acrylic fibers in the amount of 2.5 vol. %. increase the flexural strength by 28% and the flexural toughness by 240% [8], whereas steel fibers in the amount of 1.2 vol. % strength increase the flexural strength by 41% and the flexural toughness by 1500% [9]. In spite of the large fiber volume fractions, acrylic and steel fibers yield fractional increases in the flexural strength that are lower than that of the carbon fibers of this work (0.2 vol. %). However, acrylic and steel fibers of such large volume fractions yield fractional increases in the flexural toughness that are higher than that of 0.2 vol. % carbon fibers. In addition to the better effectiveness in increasing the flexural strength, carbon fibers are attractive in their chemical stability.

CONCLUSION

A formulation for carbon fiber reinforced concrete has been developed. This formulation uses short pitch-based carbon fibers in the amount of 0.5% of the weight of the cement. In addition, it uses Dis + Chem + silica fume A. In the case of Concrete D, which uses the #57 aggregate, the carbon fibers amount to 0.189 vol. % of the concrete. Compared to plain concrete, this formulation costs 39% more in materials and yields a flexural strength increase of 85% and a flexural toughness increase of 205% at 28 days of curing. When an air entrainer is used, this formulation, compared to plain air-entrained concrete, yields a flexural strength increase of 79% and a flexural toughness increase of 53% at 28 days of curing. Hence, the formulation works well for increasing the flexural strength, whether or not an air entrainer is used, but it is much more effective for increasing the flexural toughness when an air entrainer is not used. The increase in flexural toughness is due to the increase in both the flexural strength and the ductility.

The aggregate size has little effect on the effectiveness of the abovementioned formulation.

The minimum carbon fiber volume fraction for the fibers to be effective for increasing the flexural strength is 0.1%.

The optimum fiber length is such that the mean fiber length decreases from 12 mm before mixing to 7 mm after mixing. The fiber length decrease occurs in the Hobart mixer stage of the mixing procedure.

The optimum water/cement ratio is 0.50 (slump = 4 in) when an air entrainer is not used, and is 0.45 (slump = 2 in) when an air entrainer is used. The slump of the corresponding plain concrete of the same water/cement ratio is 6 in.

The use of Dis (methylcellulose + a defoamer) refers to a wet mixing (in water) procedure. Dispersing the fibers by dry mixing (without Dis) gives similar results, but it is tedious compared to dispersing the fibers in water.

The air content is significantly increased by the fiber addition, whether or not an air entrainer is used. As a consequence, the compressive strength is decreased by the fiber addition, unless Chem and silica fume A are also used. As another consequence, the freeze-thaw durability is increased by the fiber addition, even in the absence of an air entrainer.

The drying shrinkage is decreased by the addition of fibers + Dis + Chem + silica fume A by 90% at 14 days of curing.

The electrical resistivity is decreased by the fiber addition.

This work differs from previous carbon fiber work in that it uses much less carbon fibers to achieve a similar fractional increase in the flexural strength and that previous work is essentially all on mortar only (not concrete).

FUTURE WORK

1. Development of carbon fiber reinforced concrete containing carbon fibers in the amount of 1.0% of weight of cement.
2. Measurement of the freeze-thaw durability.
3. Field testing.

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Appendix A

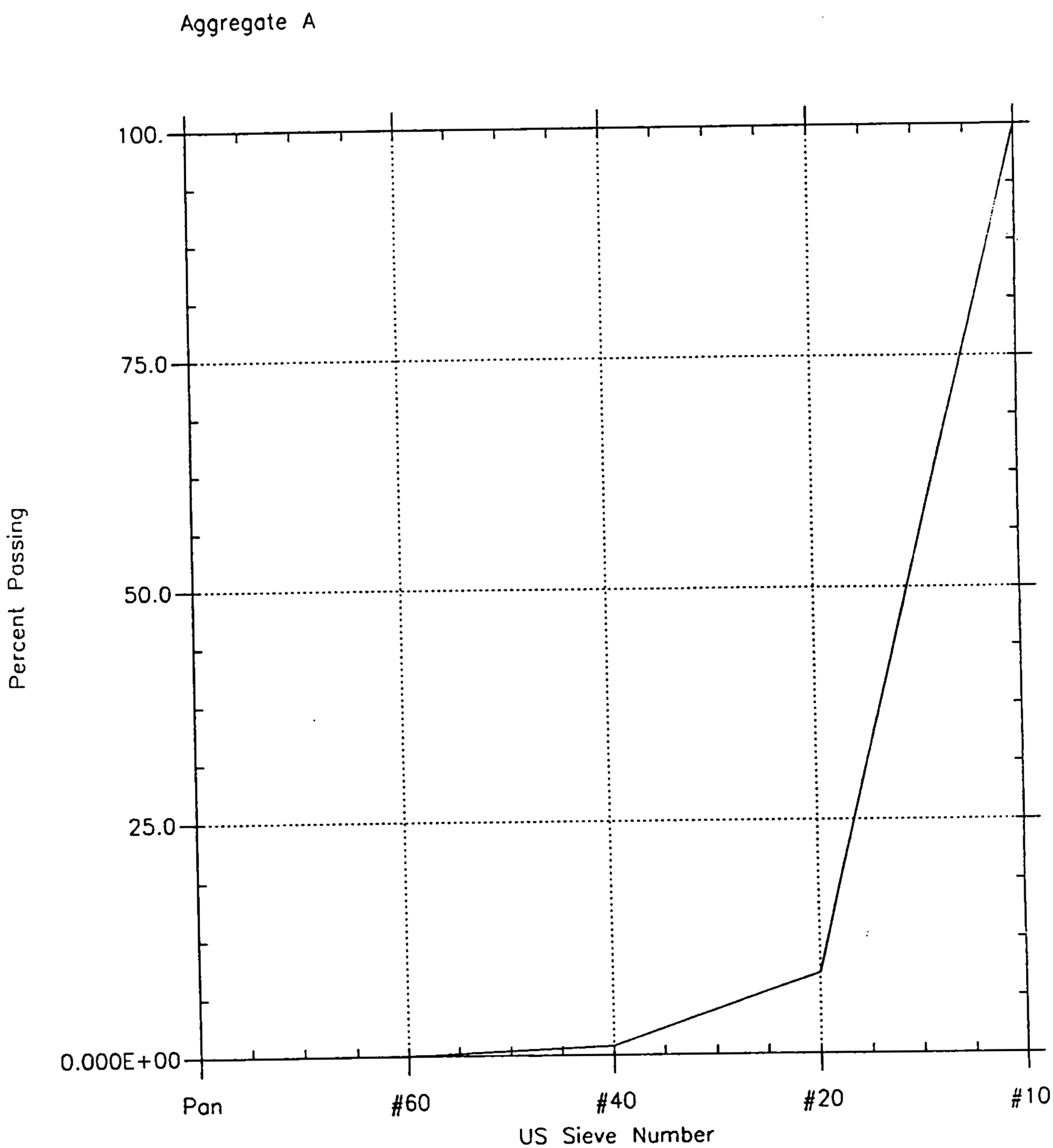

Aggregate A
Percent Passing
100.
75.0
50.0
25.0
0.000E+00
Pan
#60
#40
#20
#10
US Sieve Number

Fig. 1(a)

Aggregate B

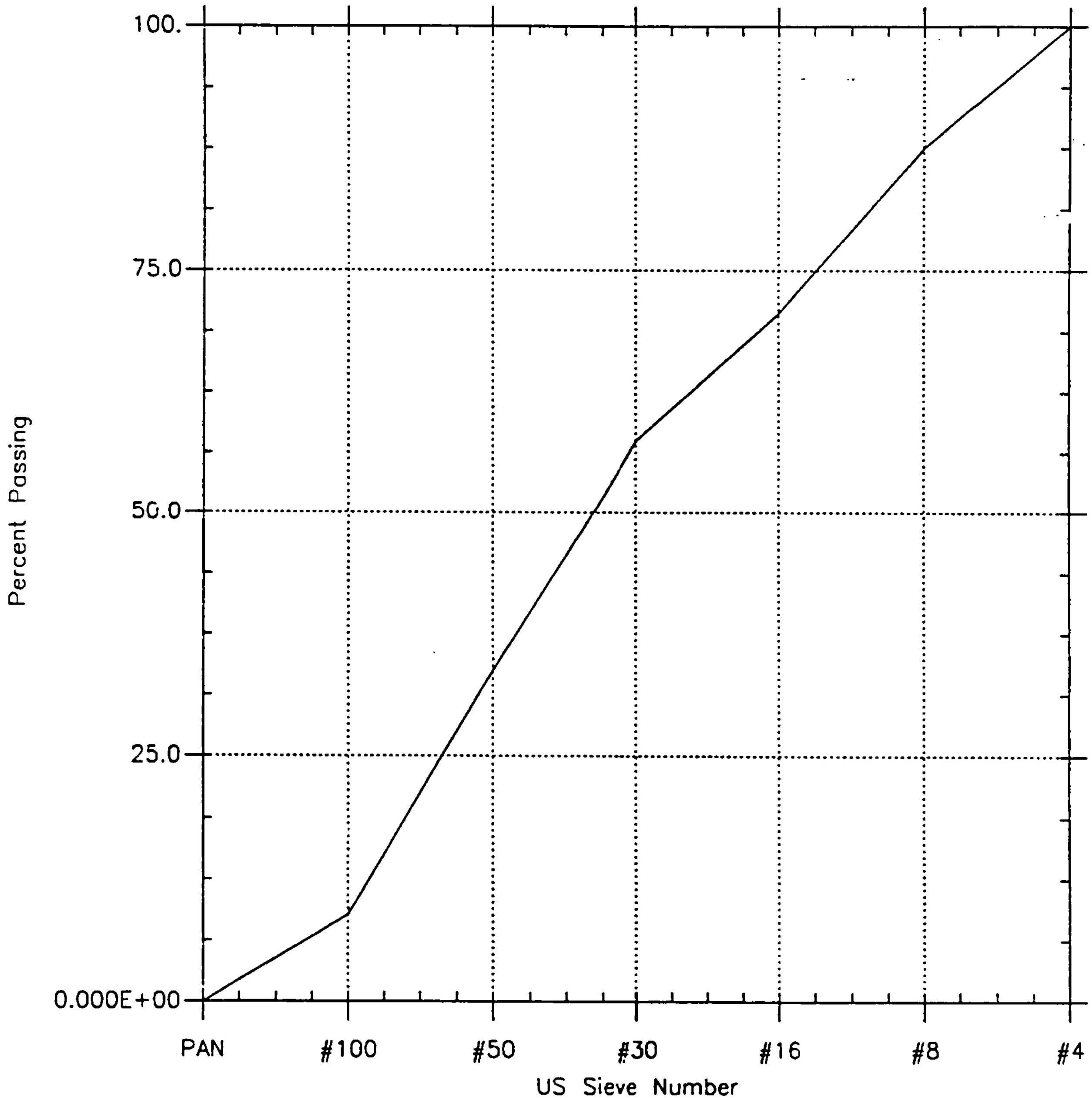
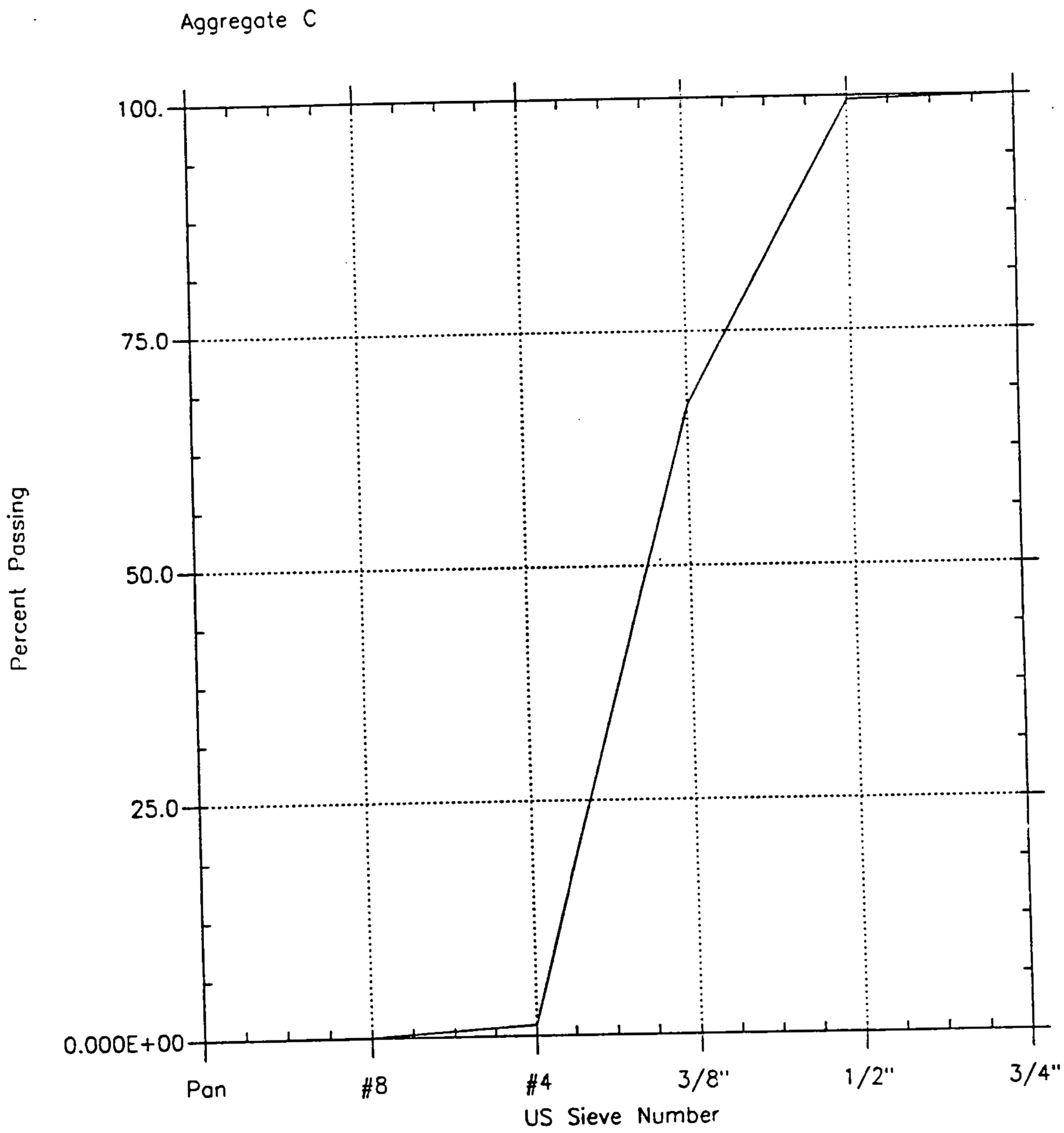


Fig. 1(b)



Aggregate C
100.
75.0
50.0
25.0
0.000E+00
Percent Passing
Pan
#8
#4
3/8"
1/2"
3/4"
US Sieve Number

Fig. 1(c)

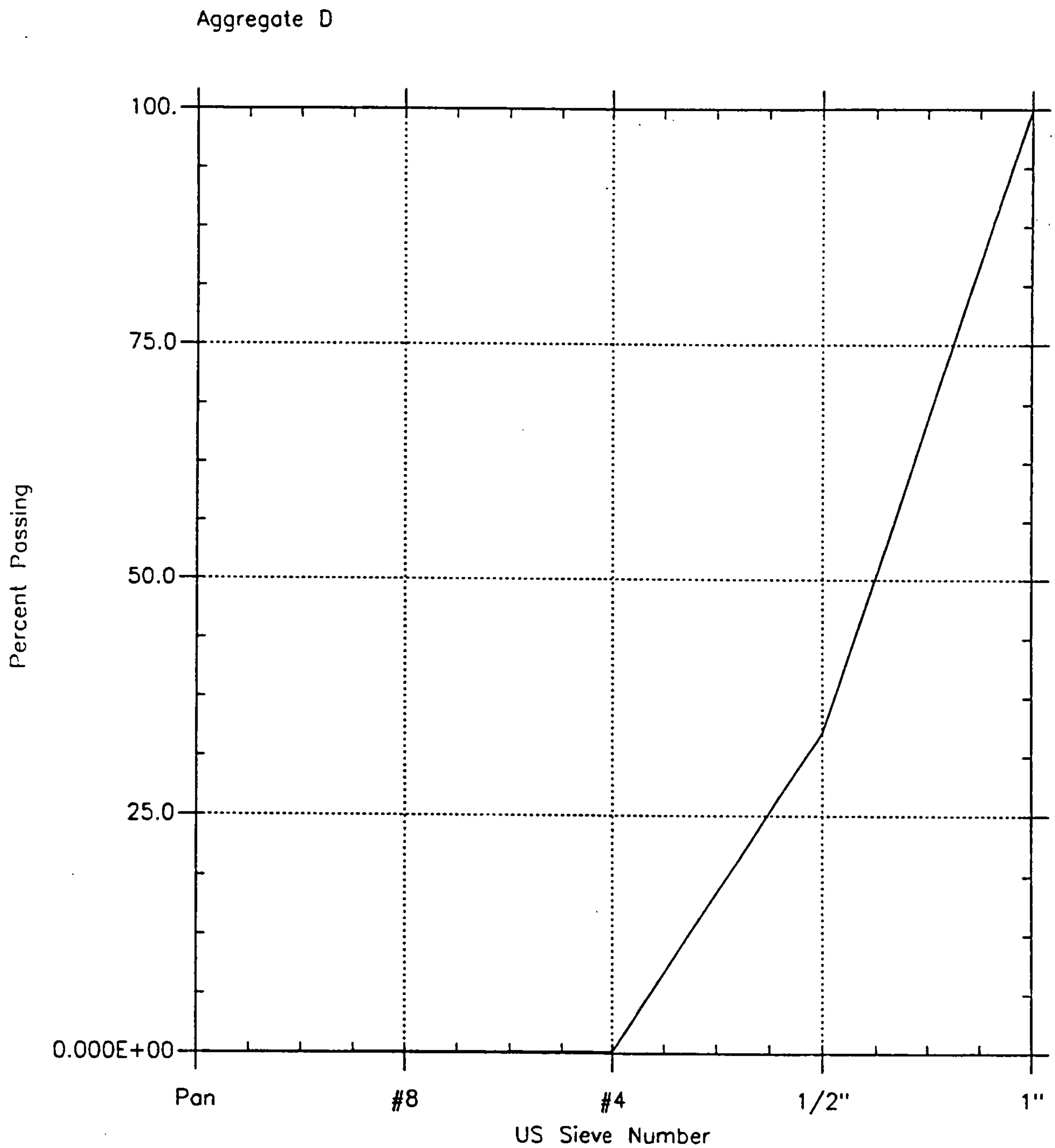

Aggregate D
100.
75.0
50.0
25.0
0.000E+00
Percent Passing
Pan
#8
#4
1/2"
1"
US Sieve Number

Fig. 1(d)

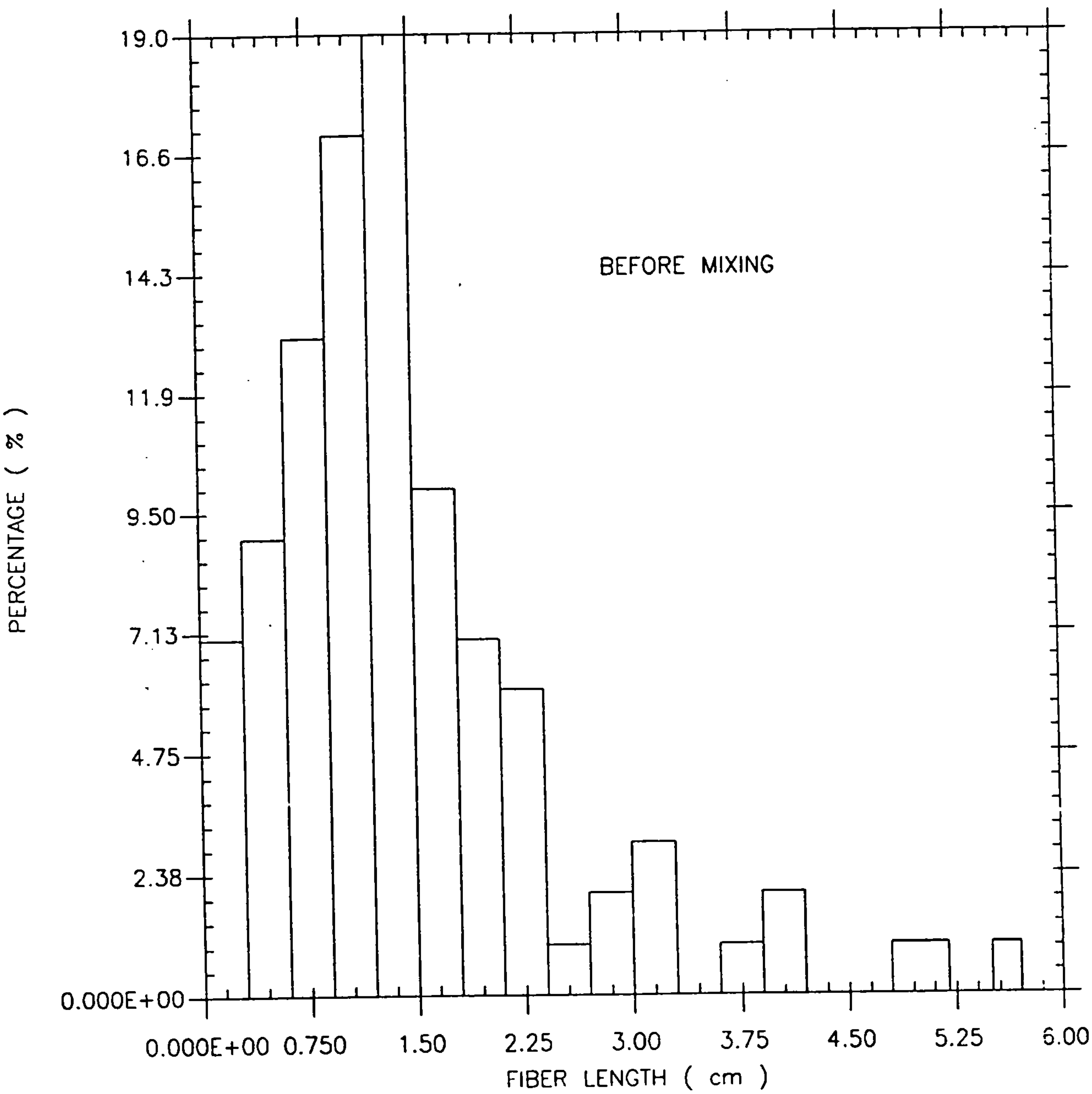

19.0
16.6
14.3
11.9
9.50
7.13
4.75
2.38
0.000E+00
PERCENTAGE (%)
BEFORE MIXING
0.000E+00 0.750 1.50 2.25 3.00 3.75 4.50 5.25 6.00
FIBER LENGTH (cm)

Fig. 2(a)

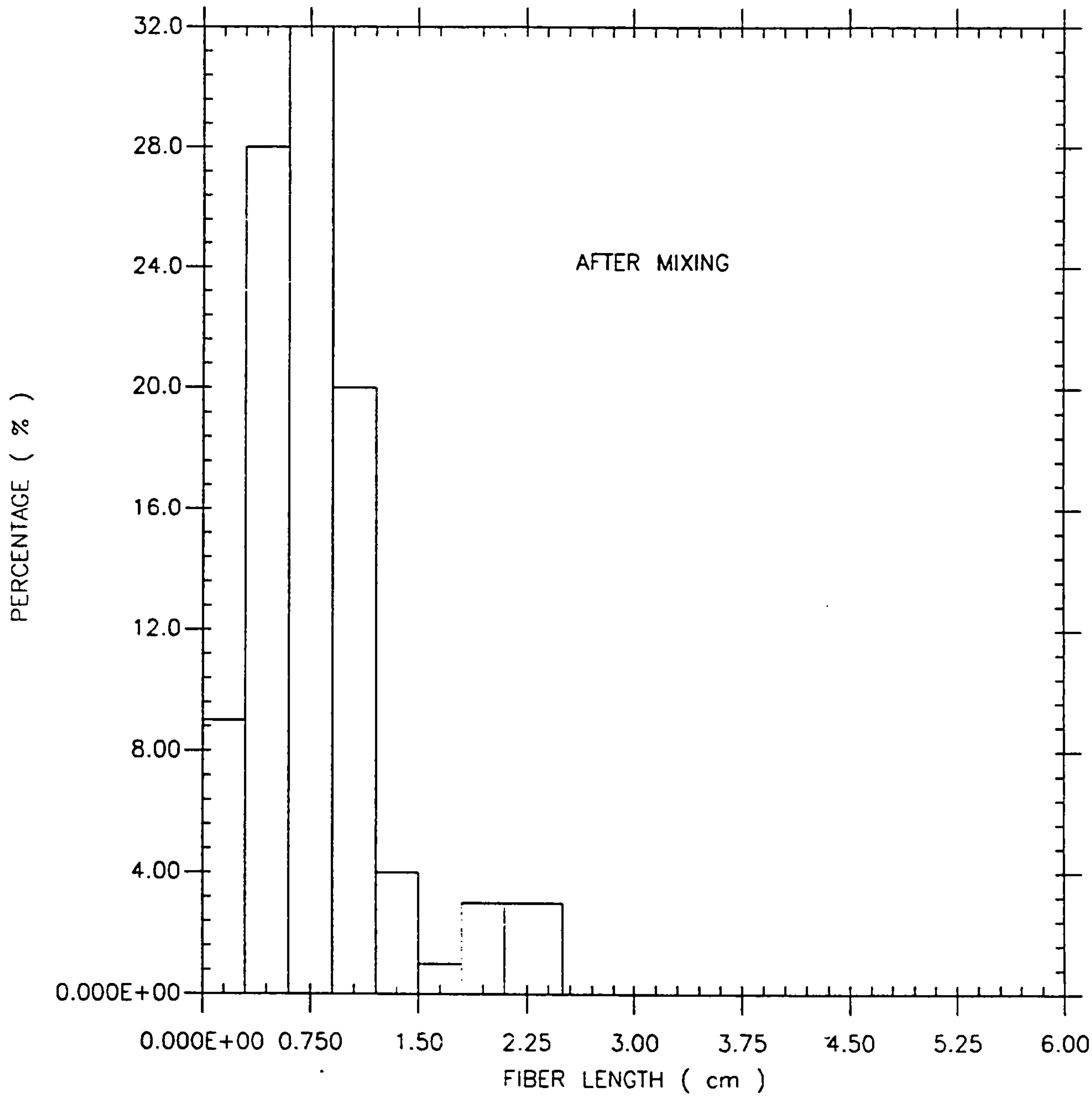

32.0
28.0
24.0
20.0
16.0
12.0
8.00
4.00
0.000E+00
PERCENTAGE (%)
AFTER MIXING
0.000E+00 0.750 1.50 2.25 3.00 3.75 4.50 5.25 6.00
FIBER LENGTH (cm)

Fig. 2(b)

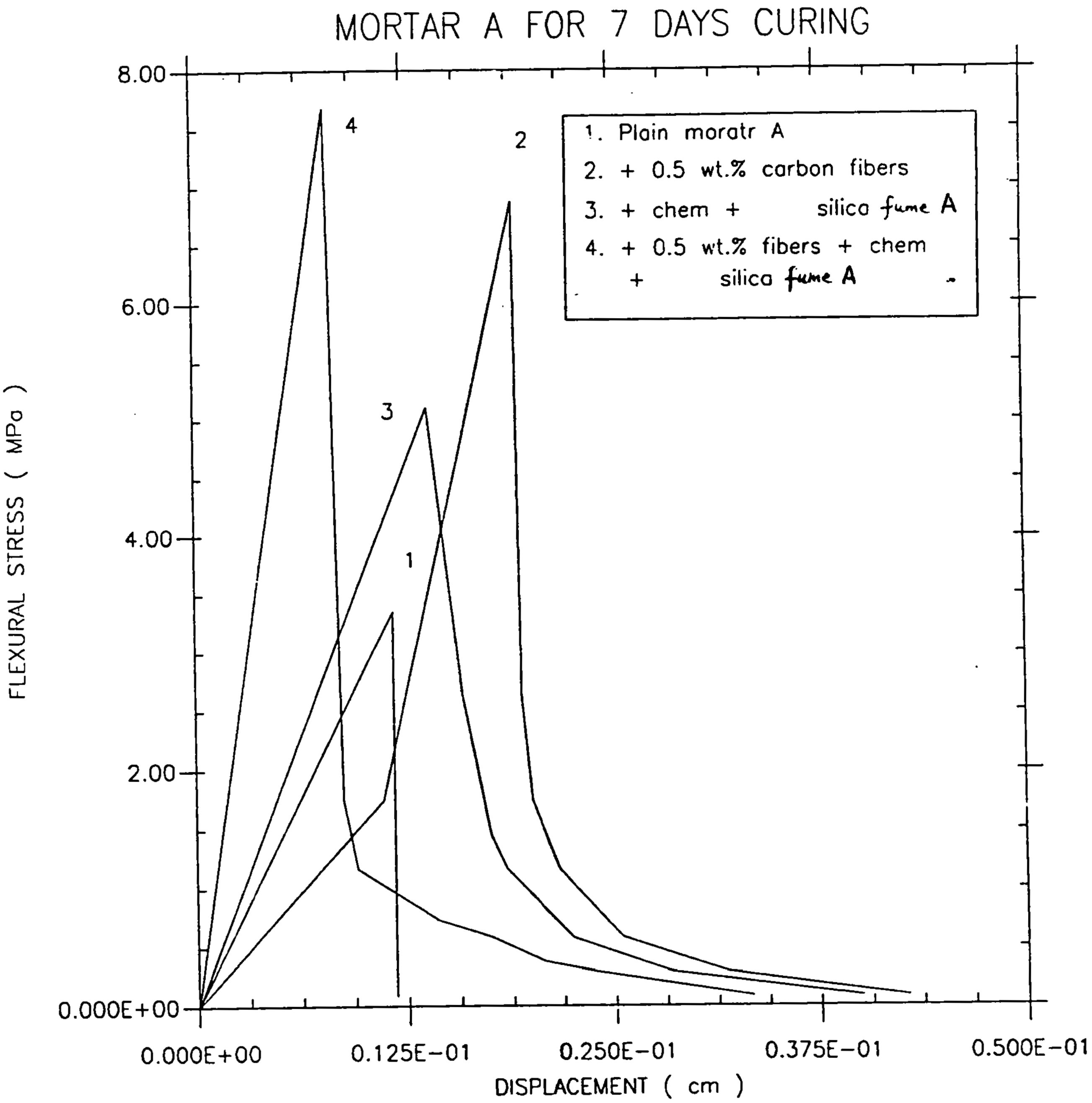

MORTAR A FOR 7 DAYS CURING
8.00
6.00
4.00
2.00
0.000E+00
0.000E+00
0.125E-01
0.250E-01
0.375E-01
0.500E-01
DISPLACEMENT (cm)
FLEXURAL STRESS (MPa)
1
2
3
4
1. Plain moratr A
2. + 0.5 wt.% carbon fibers
3. + chem + silica fume A
4. + 0.5 wt.% fibers + chem + silica fume A

Fig. 3(a)

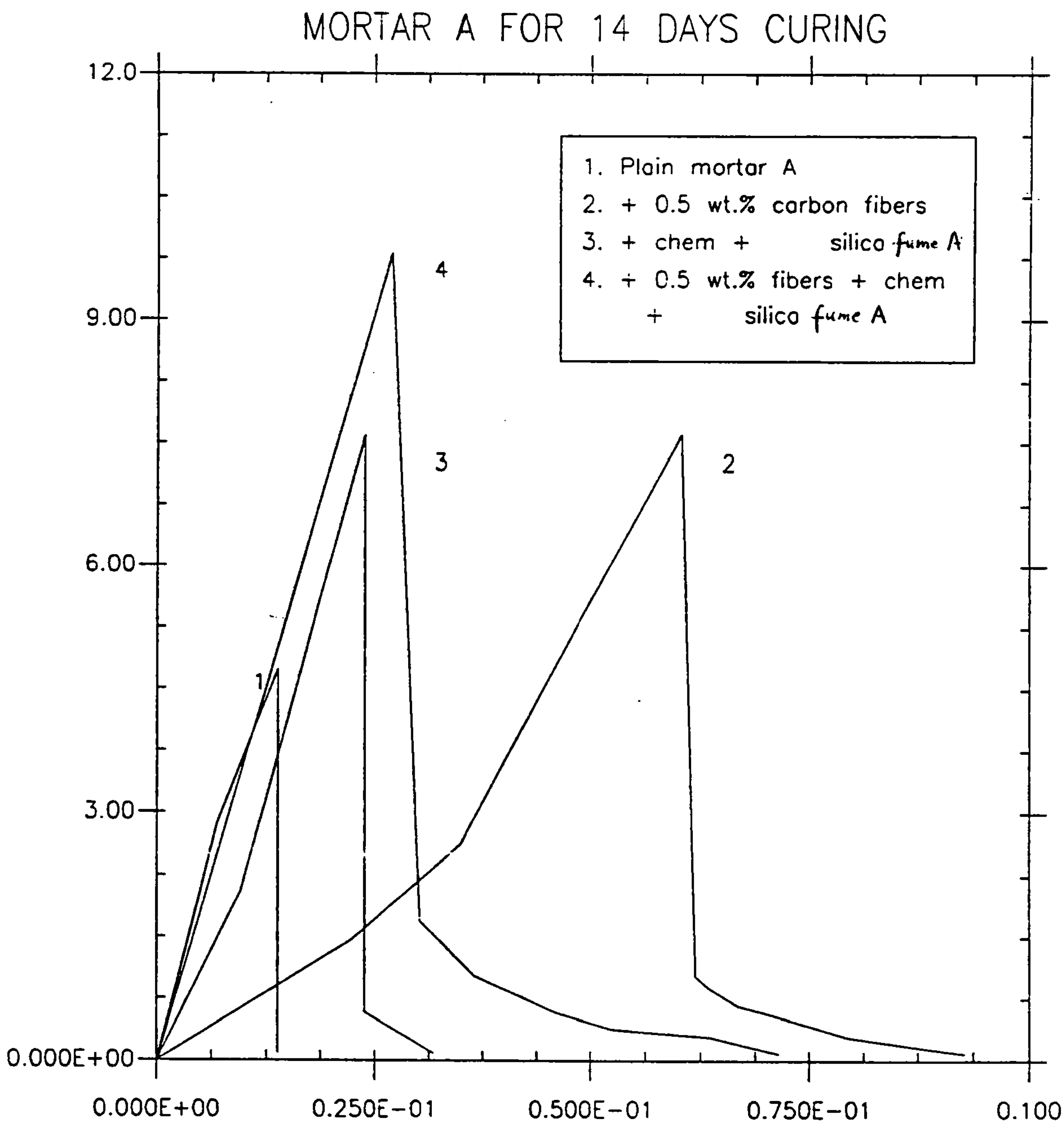

MORTAR A FOR 14 DAYS CURING
1. Plain mortar A
2. + 0.5 wt.% carbon fibers
3. + chem + silica fume A
4. + 0.5 wt.% fibers + chem + silica fume A
12.0
9.00
6.00
3.00
0.000E+00
0.000E+00
0.250E-01
0.500E-01
0.750E-01
0.100
1
2
3
4

Fig. 3(b)

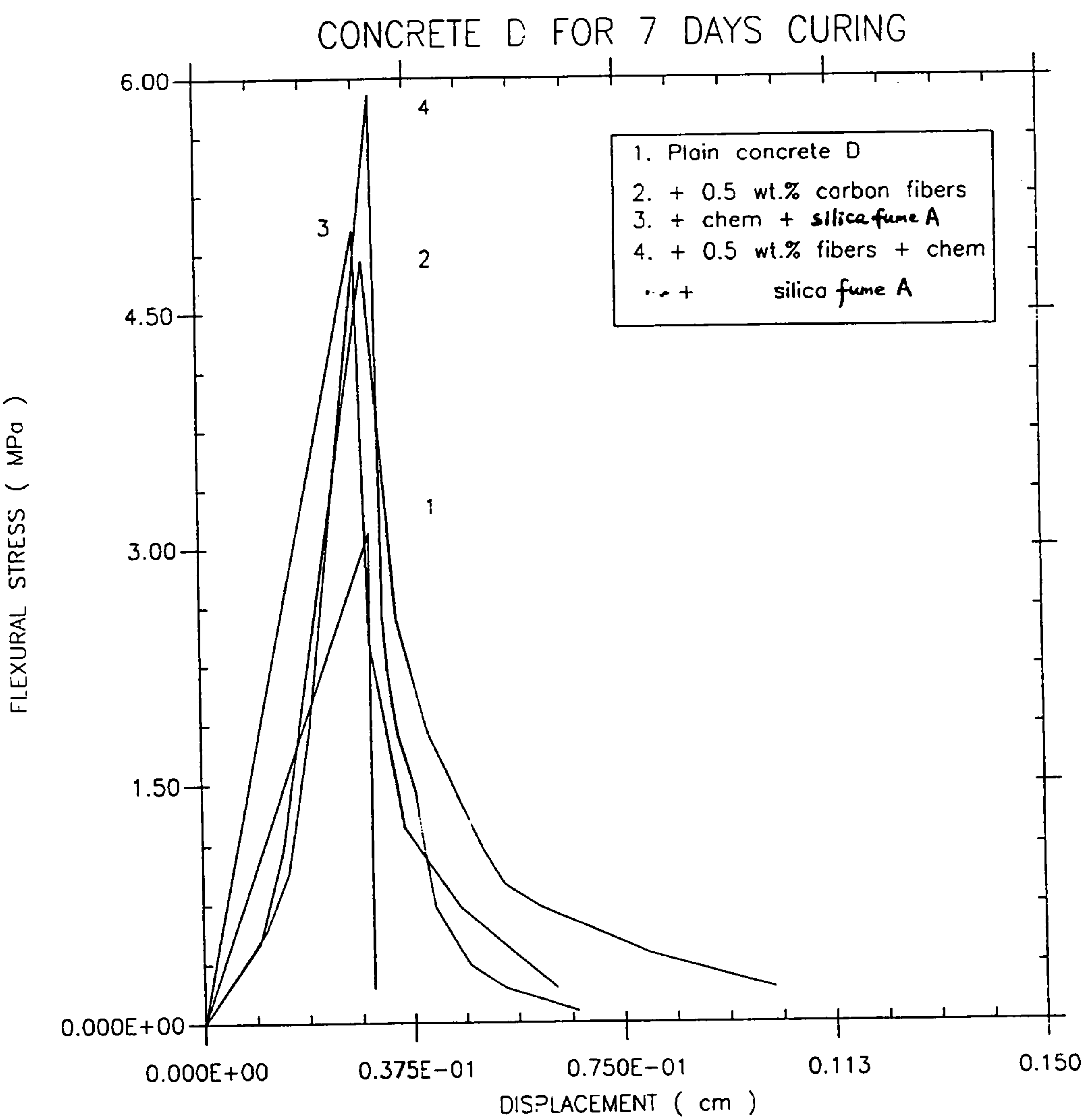

CONCRETE D FOR 7 DAYS CURING
6.00
4.50
3.00
1.50
0.000E+00
FLEXURAL STRESS (MPa)
0.000E+00
0.375E-01
0.750E-01
0.113
0.150
DISPLACEMENT (cm)
1. Plain concrete D
2. + 0.5 wt.% carbon fibers
3. + chem + silica fume A
4. + 0.5 wt.% fibers + chem
+ silica fume A
1
2
3
4

Fig. 4(a)

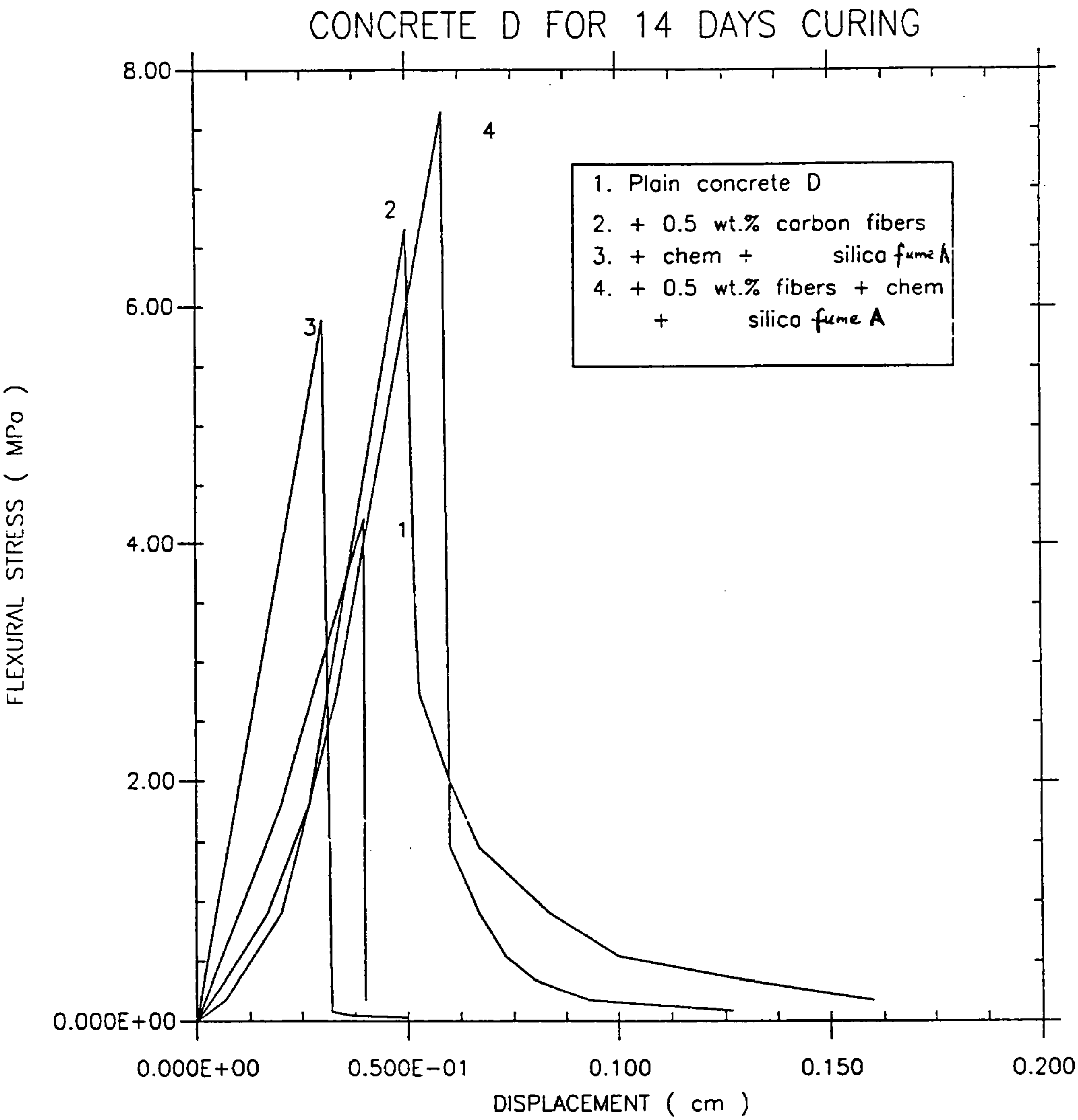

CONCRETE D FOR 14 DAYS CURING
8.00
6.00
4.00
2.00
0.000E+00
FLEXURAL STRESS (MPa)
0.000E+00
0.500E-01
0.100
0.150
0.200
DISPLACEMENT (cm)
1
2
3
4
1. Plain concrete D
2. + 0.5 wt.% carbon fibers
3. + chem + silica fume A
4. + 0.5 wt.% fibers + chem
+ silica fume A

Fig. 4(b)

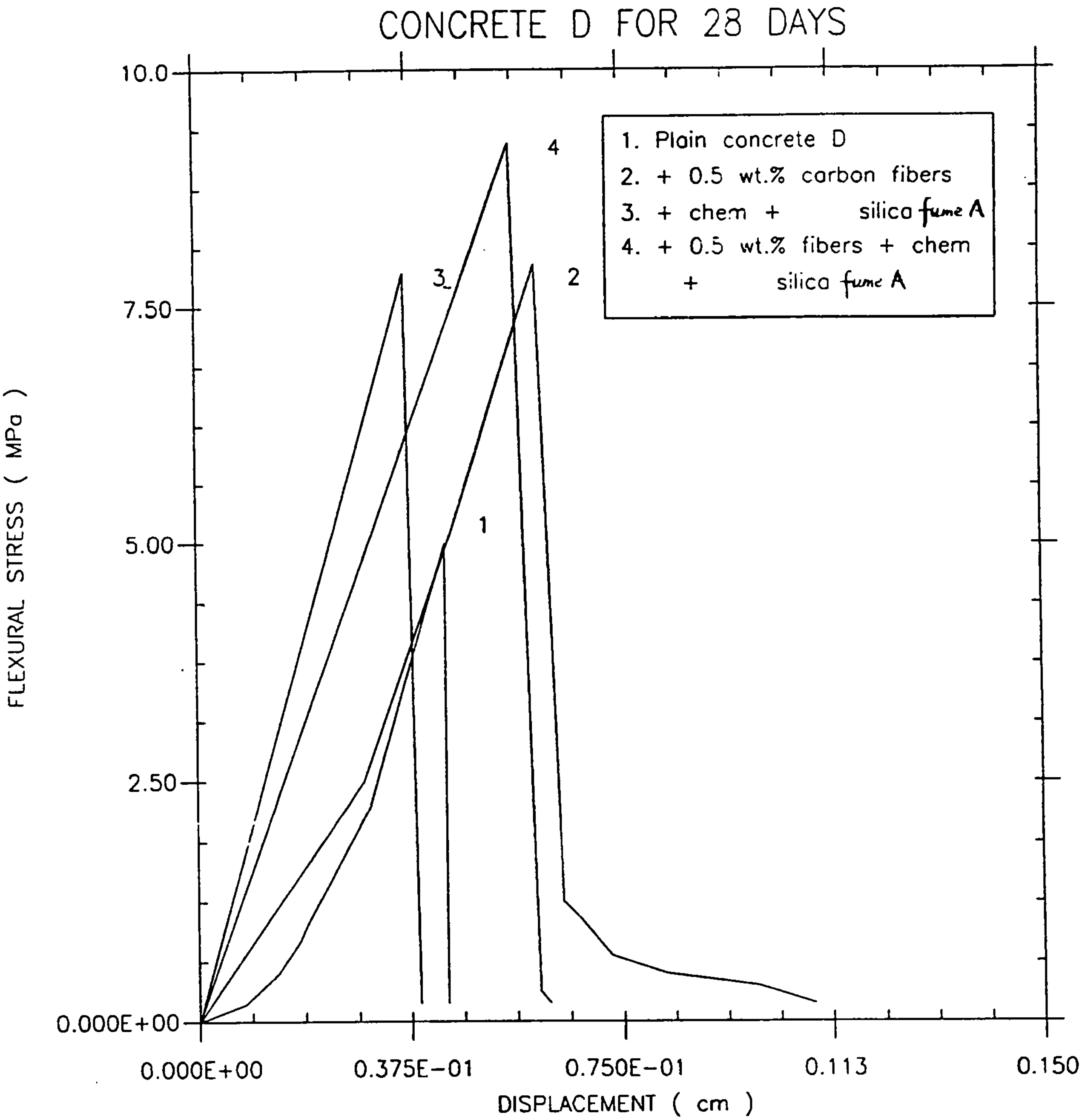

CONCRETE D FOR 28 DAYS
1. Plain concrete D
2. + 0.5 wt.% carbon fibers
3. + chem + silica fume A
4. + 0.5 wt.% fibers + chem + silica fume A
10.0
7.50
5.00
2.50
0.000E+00
FLEXURAL STRESS (MPa)
0.000E+00
0.375E-01
0.750E-01
0.113
0.150
DISPLACEMENT (cm)

Fig. 4(c)

curing in moist room for 90 days

specimen size : 4"D x 8"L cylinder

W/C = 0.5

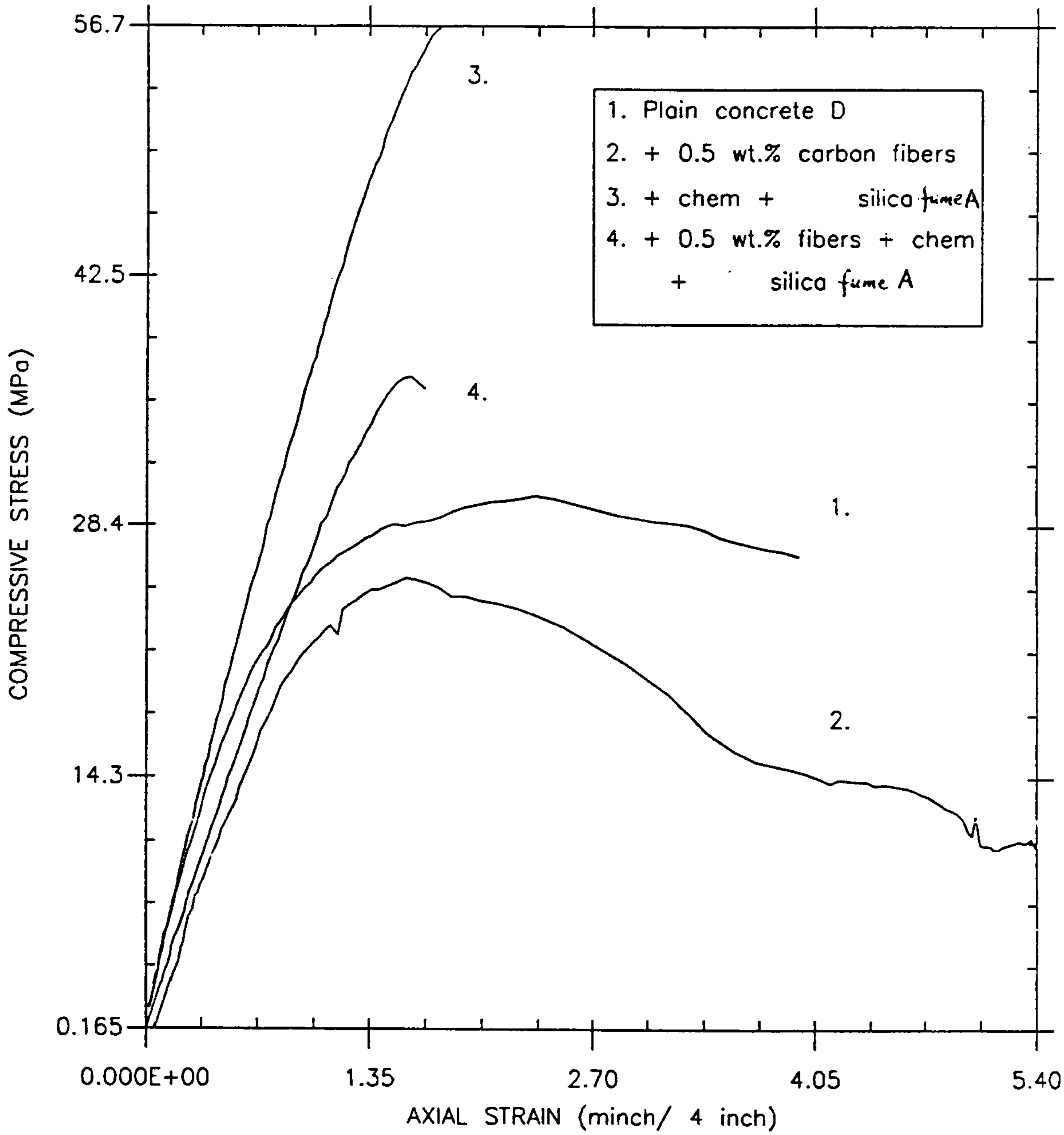


Fig. 5(a)

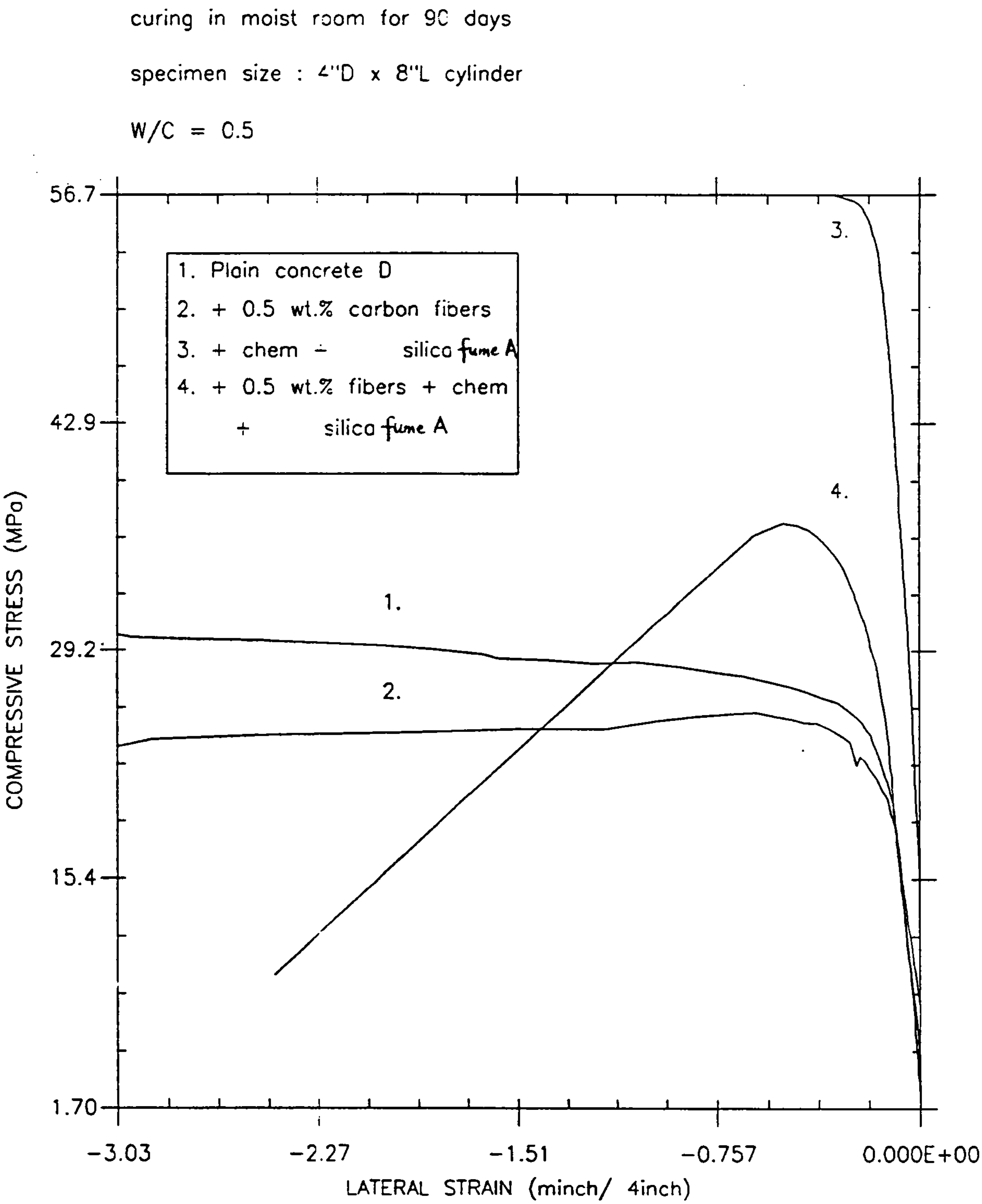
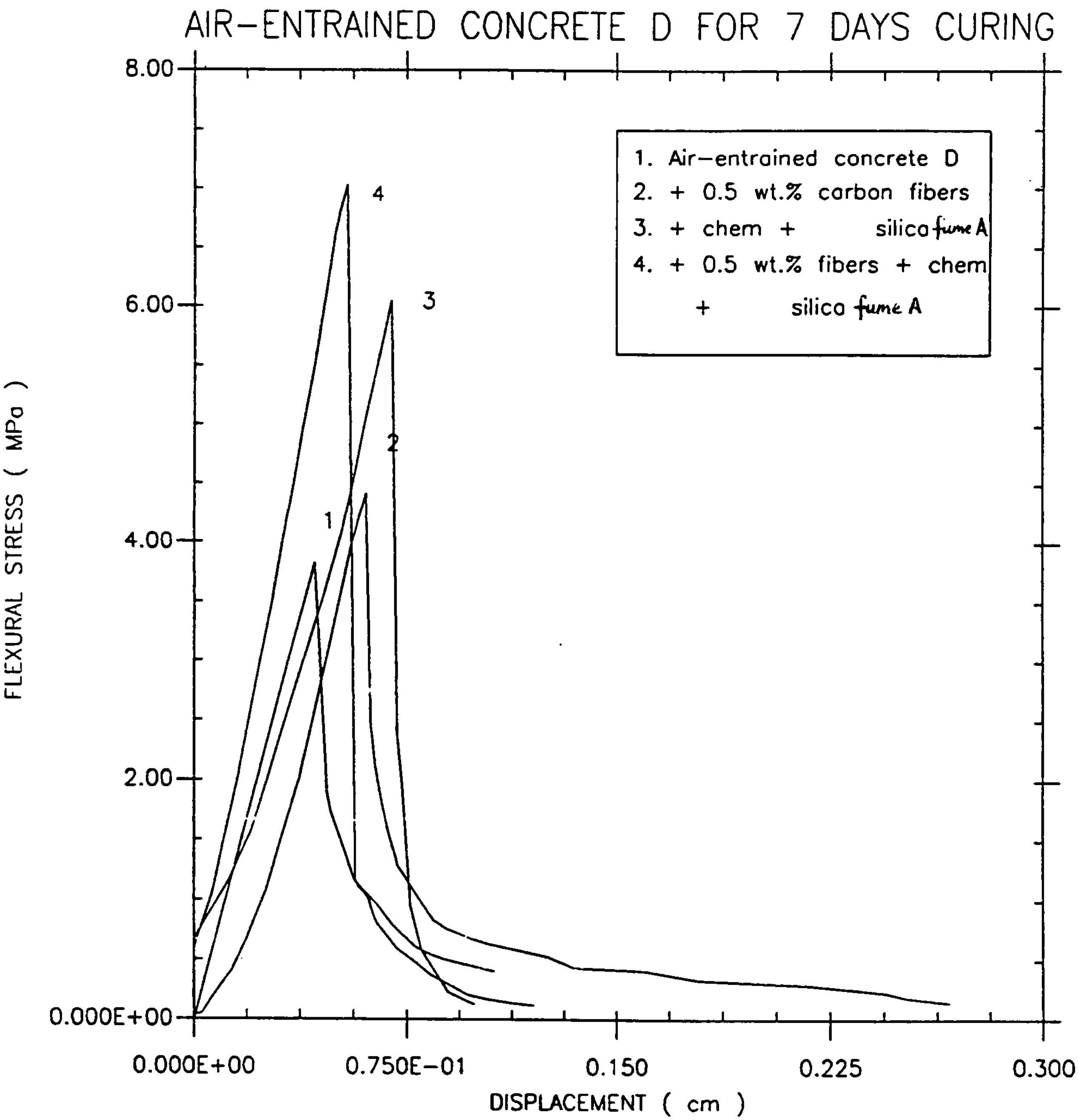

curing in moist room for 90 days
specimen size : 4"D x 8"L cylinder
W/C = 0.5
1. Plain concrete D
2. + 0.5 wt.% carbon fibers
3. + chem + silica fume A
4. + 0.5 wt.% fibers + chem
+ silica fume A
COMPRESSIVE STRESS (MPa)
56.7
42.9
29.2
15.4
1.70
-3.03
-2.27
-1.51
-0.757
0.000E+00
LATERAL STRAIN (minch/ 4inch)
1.
2.
3.
4.

Fig. 5(b)

W/C = 0.45



AIR-ENTRAINED CONCRETE D FOR 7 DAYS CURING
1. Air-entrained concrete D
2. + 0.5 wt.% carbon fibers
3. + chem + silica fume A
4. + 0.5 wt.% fibers + chem + silica fume A
FLEXURAL STRESS (MPa)
DISPLACEMENT (cm)
8.00
6.00
4.00
2.00
0.000E+00
0.000E+00
0.750E-01
0.150
0.225
0.300
1
2
3
4

Fig. 6(a)

W/C = 0.45

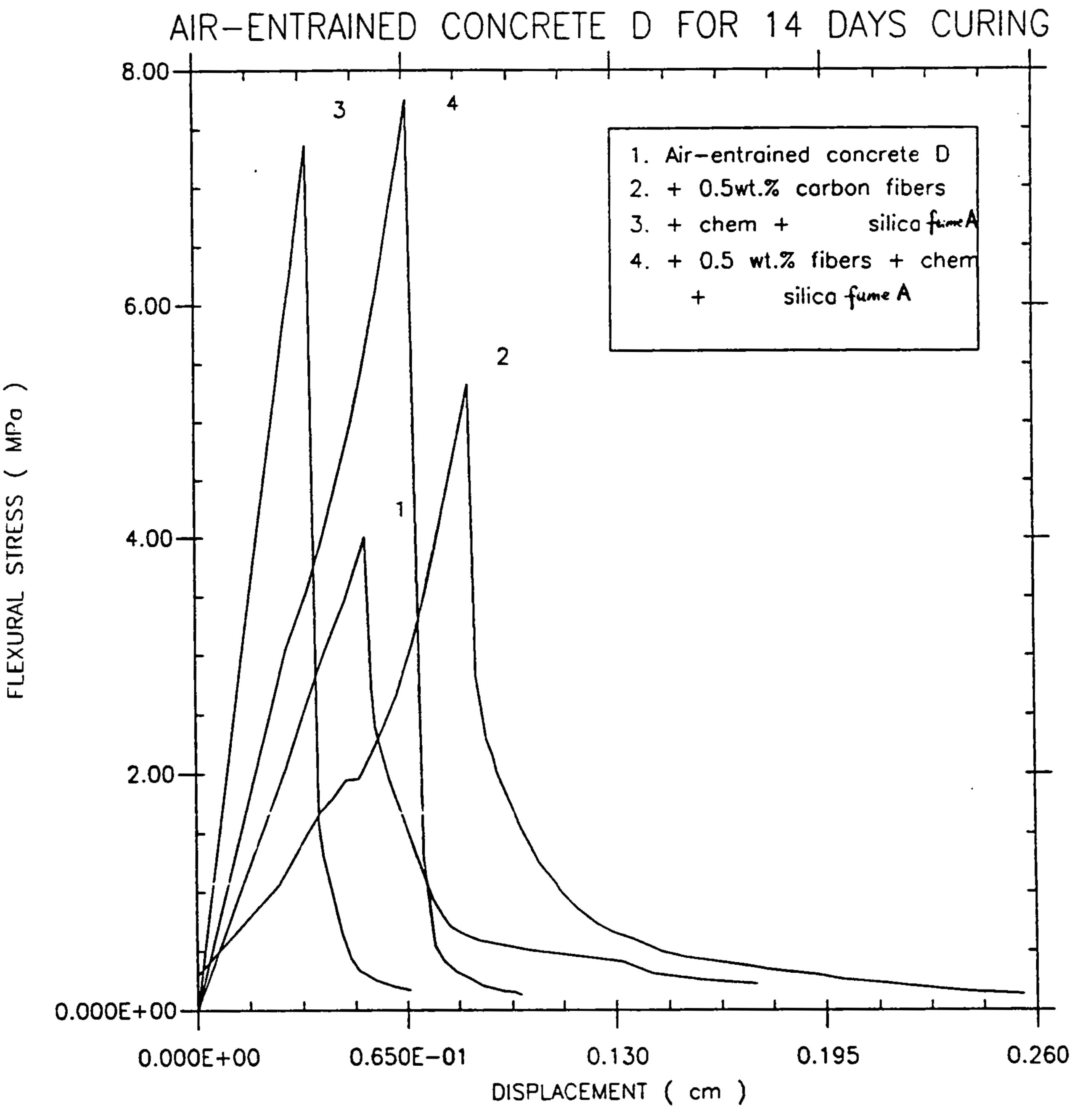

AIR-ENTRAINED CONCRETE D FOR 14 DAYS CURING
FLEXURAL STRESS (MPa)
DISPLACEMENT (cm)
8.00
6.00
4.00
2.00
0.000E+00
0.000E+00
0.650E-01
0.130
0.195
0.260
1
2
3
4
1. Air-entrained concrete D
2. + 0.5wt.% carbon fibers
3. + chem + silica fume A
4. + 0.5 wt.% fibers + chem + silica fume A

Fig. 6(b)

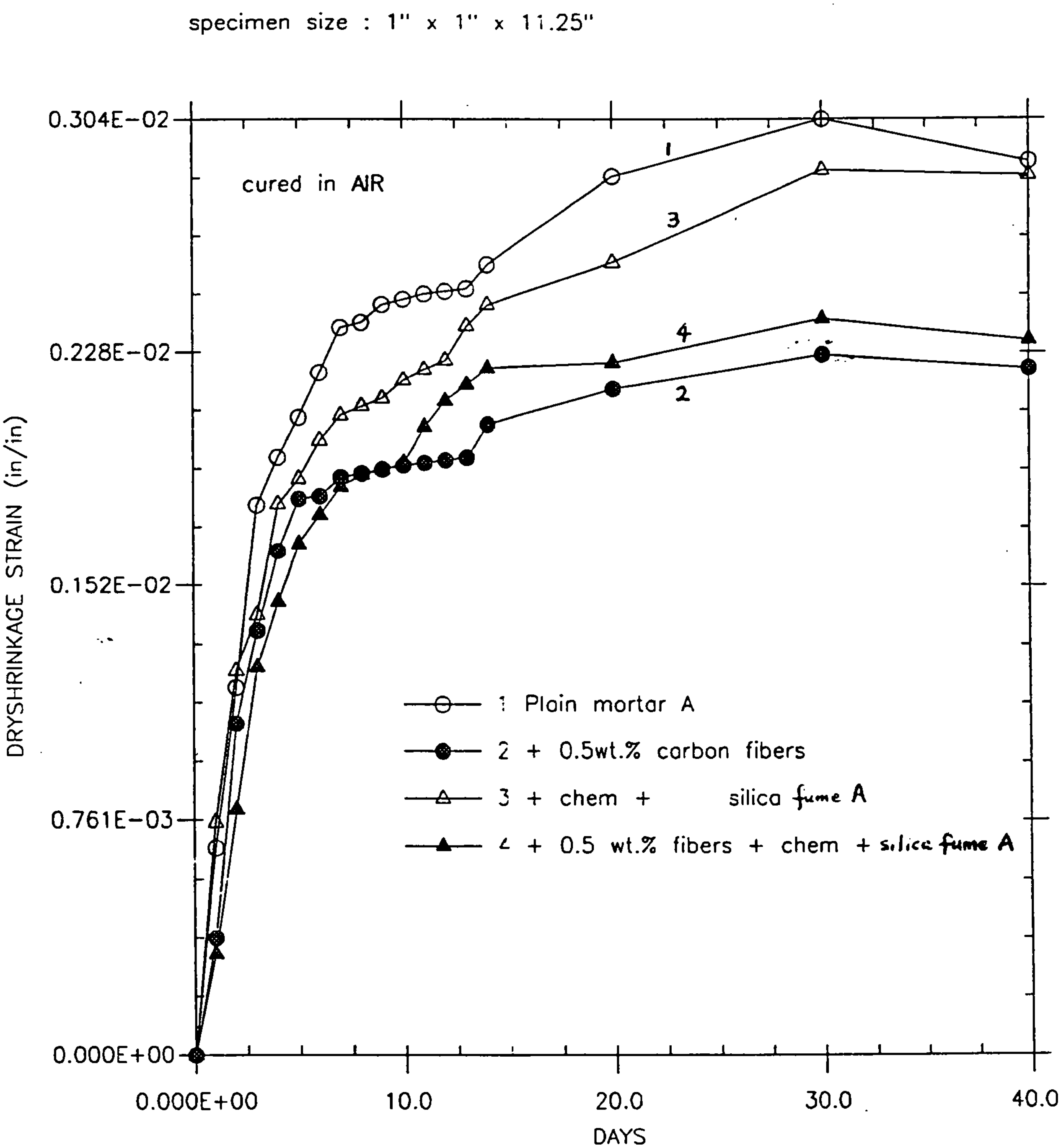
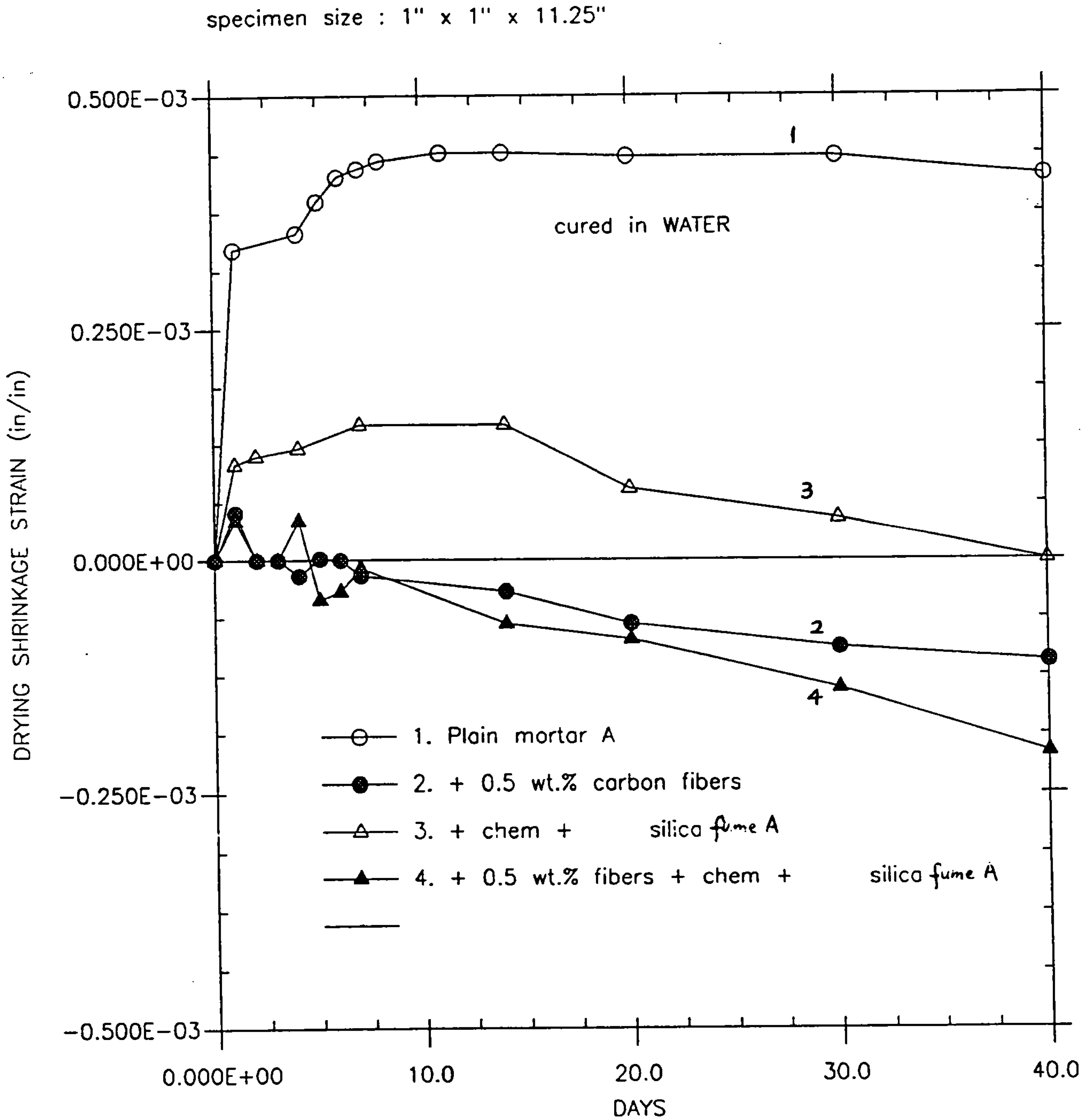
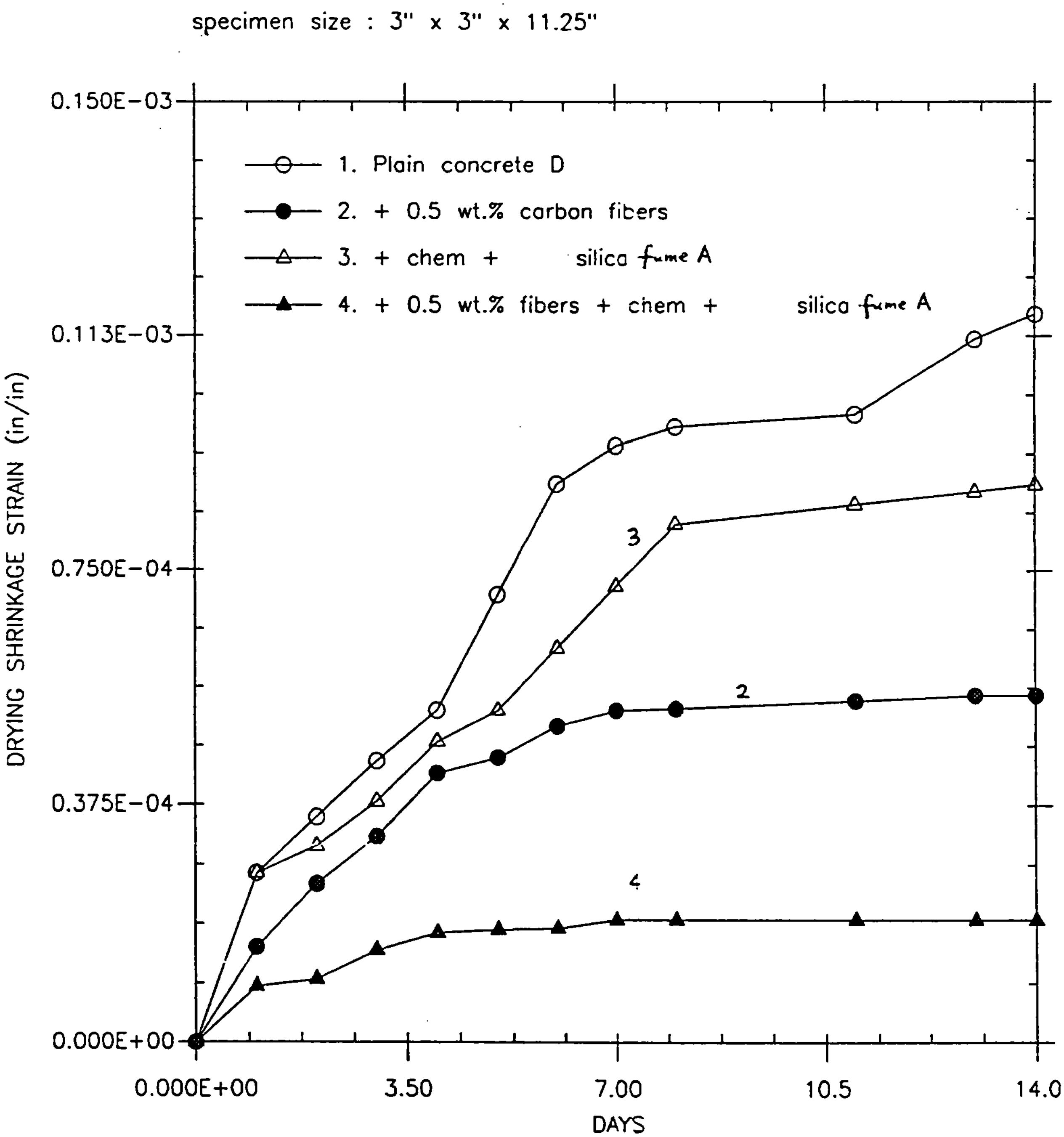

specimen size : 1" x 1" x 11.25"
cured in AIR
0.304E−02
0.228E−02
0.152E−02
0.761E−03
0.000E+00
DRYSHRINKAGE STRAIN (in/in)
0.000E+00
10.0
20.0
30.0
40.0
DAYS
1
3
4
2
1 Plain mortar A
2 + 0.5wt.% carbon fibers
3 + chem + silica fume A
4 + 0.5 wt.% fibers + chem + silica fume A

Fig. 7(a)



specimen size : 1" x 1" x 11.25"
0.500E−03
0.250E−03
0.000E+00
−0.250E−03
−0.500E−03
DRYING SHRINKAGE STRAIN (in/in)
0.000E+00
10.0
20.0
30.0
40.0
DAYS
cured in WATER
1
2
3
4
1. Plain mortar A
2. + 0.5 wt.% carbon fibers
3. + chem + silica fume A
4. + 0.5 wt.% fibers + chem + silica fume A

Fig. 7(b)



specimen size : 3" x 3" x 11.25"
1. Plain concrete D
2. + 0.5 wt.% carbon fibers
3. + chem + silica fume A
4. + 0.5 wt.% fibers + chem + silica fume A
0.150E-03
0.113E-03
0.750E-04
0.375E-04
0.000E+00
DRYING SHRINKAGE STRAIN (in/in)
0.000E+00
3.50
7.00
10.5
14.0
DAYS
3
2
4

Fig. 8

Appendix B

Table 1. Comparing this work to previous work on carbon fiber reinforced mortar.

Reference	Fiber* Vol.%	Flexural Strength† increase(%)	Fiber Length (mm)	W/C‡	Sand/C	Silica Fume/C	Methylcellulose /C (%)	Water reducing/C	Admixtures
Furukawa (1987)	1	10	6	0.32	0.504	0.4	--	--	--
	1	32	6	0.40	1	0.4	--	--	--
Akihama (Feb.1986)	1.72	46	10	0.42	--	--	1	--	--
	1.72	25	10	0.473	0.25	--	1	--	--
	1.72	97	10	0.527	0.50	--	1	--	--
Akihama (Oct.1986)	2.1	150	3	0.473	0.25	--	1	--	--
Ohama (1986)	[illegible]	56	6	0.3	--	0.4	--	6%	--
Park (1990)	1	16	3	0.3	0.4	--	--	--	Superplasticizer /cement = 6%
	1	20	10	0.3	0.4	--	--	--	Superplasticizer /cement = 6%
This work	0.244	105	5	0.45	1.5	--	0.4	2%	Dis
	0.244	50	5	0.45	1.5	0.15	0.4	2%	Dis + Chem +silica fume A

* Pitch-based carbon fibers

† 7 days of curing in air or water, 20-25°C, 60-100 RH; the increase is relative to the same mortar without carbon fibers.

‡ C = cement

Dis =dispersant, consisting of
Methylcellulose (0.4% of cement wt.)
Colloids 1010 (0.13 vol.%)

Chem =chemical agents, consisting of
triethanolamine (0.06% of cement wt.)
potassium aluminum sulfate (0.5% of cement wt.)
sodium sulfate (0.5% of cement wt.)
water reducing agent

Table 2. Comparing this work to previous work on carbon fiber reinforced concrete.

Reference	Fiber Vol.%	Flexural Strength (MPa)	W/C	Aggreg/C	Fine Aggreg/C	Coarse Aggreg/C	Water Reducing/C	Admixtures	Curing Conditions
Akihama (Oct.1986)	0	4.5	0.44	0.45	2.57	2.01	/	Not disclosed (1%)	
	2.5 (3 mm)	7.6	0.737	0.295 aggregate =micro-balloons +silica fume +silica powder	/	/	1.2%	/	Cured with moisture at 40°C for 7 h., then autoclaved at 180°C and 10 atm for 5 h.
This work	0	5.00	0.5	/	1.5	2.49	/	/	Cured in moist room
	0	7.86	0.5	/	1.5	2.49	2%	Chem + silica fume A	
	0.189 (5mm)	7.95	0.5	/	1.5	2.49	2%	Dis	
	0.189 (5mm)	9.23	0.5	/	1.5	2.49	2%	Dis+Chem +silica fume A	

* Pitch-based carbon fibers

Dis = dispersant, consisting of
methylcellulose (0.4% of cement wt.)
Colloids 1010 (0.13 vol.%)

Chem =chemical agents, consisting of
triethanolamine (0.06% of cement wt.)
potassium aluminum sulfate (0.5% of cement wt.)
sodium sulfate (0.5% of cement wt.)
water reducing agent

Table 3 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 4 Catalog of aggregates

Label	Description
Aggregate A	#2 silica sand
Aggregate B	Standard aggregate for Masonry Mortar ASTM C144-81 100% passed #4 standard sieve
Aggregate C	#7 aggregate ASTM C33-84 100% passed 3/4" standard sieve
Aggregate D	#57 aggregate ASTM C33-84 100% passed 1" standard sieve Commonly used for highway pavements

Table 5 Aggregates in mortars and concretes

Label	Aggregate(s) used
Mortar A	Aggregate A
Mortar B	Aggregate B
Concrete C	Aggregates B + C
Concrete D	Aggregates B + D

Table 6 List of raw materials

Material	Source
Portland cement (Type I)	Lafarge Corporation (Southfield, MI)
Silica sand, #2 (crystalline) (99.91% SiO_2)	Pennsylvania Glass Sand Corporation (Berkeley Springs, WV)
TAMOL SN (Sodium salt of a condensed naphthalenesulfonic acid, 93-96%) (Water, 4-7%) (Tan free flowing powder)	Rohm and Haas Company (Philadelphia, PA)
TAMOL L (Sodium salt of a condensed naphthalenesulfonic acid, 46-49%) (Water, 51-54%) (Dark brown mobile liquid)	Rohm and Haas Company (Philadelphia, PA)
Methocel, A15-LV (Methylcellulose)	Dow Chemical (Midland, MI)
Daravair (Air-entraining admixture) (ASTM C-260)	W.R. Grace & Co. (Cambridge, MA)
Carboflex (Carbon fibers)	Ashland Petroleum Company (Ashland, KY)
Colloids 1010 (Defoamer)	Colloids Inc. (Marietta, GA)
Aluminum potassium sulfate	Fisher Scientific (Fair Lawn, NJ)
Sodium sulfate	Riverside Chemical Co. (Buffalo, NY)
Triethanolamine (85%)	Riverside Chemical Co. (Buffalo, NY)
Silical fume A	Elkem Materials Inc. (Pittsburgh, PA)
Silica fume B	TAM Ceramics (Niagara Falls, NY)

Table 7 Dry Mix: mixing procedure for Mortar B and for Concrete D+

(1) Mix carbon fibers with Aggregate B by hand (by roughly putting a layer of fibers, a layer of Aggregate B, a layer of fibers, a layer of Aggregate B, etc.)

(2) Start the Hobart mixer and then add (1) and cement (and silica fume, if applicable).

(3) Add the water reducing agent.

(4) Stir with the Hobart mixer for ~ 5 min.

(5) Dissolve accelerating agents in water.

(6) Add accelerating agents in the Hobart mixer and stir for ~ 3 min.

(7)* Pour into the stone concrete mixer

(8)* Add Aggregate D

(9)* Mix for ~ 3 min.

* for Concrete D, not for Mortar B.

+ with low fluidity.

Table 8 Wet Mix: mixing procedure for Mortar A and Concretes C and D^+

(1) Dissolve Dis (dispersant) in water.

(2) Add fibers and stir.

(3) Add Aggregate A, cement and silica fume A (for Mortar A only) or add Aggregate B, cement and silica fume A (for Concretes C and D^+ only).

(4) Add water reducing agent.

(5) Stir with the Hobart mixer for ~ 5 min.

(6) Add chemical agents in the Hobart mixer and stir for ~ 3 min.

(7)* Pour into the stone concrete mixer.

(8)* Add Aggregate D (for Concrete D^+ only) or add Aggregate C (for Concrete C only).

(9)* Mix for ~ 3 min.

* for Concretes C and D, not for Mortar A.

$^+$ with normal fluidity.

Table 9 Raw materials for Mortar B

Water/cement = 0.6

Aggregate B/cement = 5.48

Fibers/cement = 0.5%

Water reducing agent (TAMOL L)/cement = 1%

Accelerating agents:

Triethanolamine/cement = 0.06%

Potassium aluminum sulfate/cement = 0.5%

Sodium sulfate/cement = 0.5%

Note:

Chem = chemical agents, consisting of water reducing agent and accelerating agents

Table 10 Effect of carbon fibers* and chemical agents on strength for Mortar B

	Flexural strength (MPa)		
	28 days	14 days	7 days
(1) Plain mortar	5.82 (± 9%)	4.80 (± 2%)	4.32 (± 4.5%)
(2) + Chem	6.95 (± 10%)	5.95 (± 1%)	5.10 (± 3%)
(3) + fibers	6.42 (± 6%)	5.28 (± 7.6%)	4.76 (± 1.4%)
(4) + fibers + Chem	7.03 (± 2.9%)	6.37 (± 7.6%)	5.92 (± 9.2%)

	Compressive strength (MPa)		
	28 days	14 days	7 days
(1) Plain mortar	31.38 (± 9%)	26.02 (± 2%)	18.37 (± 1%)
(2) + Chem	35.93 (± 9%)	32.84 (± 6%)	26.14 (± 4%)
(3) + fibers	34.65 (± 12.5%)	30.70 (± 3%)	24.73 (± 1%)
(4) + fibers + Chem	36.87 (± 5.5%)	31.63 (± 5%)	25.76 (± 8%)

*0.5% of weight of cement; 3.0 mm long fibers.

Table 11 Effect of carbon fiber* length on strength at 14 days for Mortar B

1. Without chemical agents

Fiber length (mm)	Strength (MPa) Flexural	Strength (MPa) Compressive
/	4.80 (± 2.3%)	26.02 (± 2%)
3.0	5.28 (± 7.6%)	30.70 (± 3%)
5.1	6.66 (± 5.4%)	34.26 (± 10%)
12.7	6.69 (± 1.7%)	20.66 (± 10%)

2. With chemical agents

Fiber length (mm)	Strength (MPa) Flexural	Strength (MPa) Compressive
/	5.95 (± 1%)	32.84 (± 6%)
3.0	6.37 (± 7.6%)	31.63 (± 5%)
5.1	6.93 (± 4.2%)	27.99 (± 3%)
12.7	6.94 (± 8.6%)	20.19 (± 20%)

* 0.5% of weight of cement.

Conclusion: The optimum fiber length is 5.1 mm.

Table 12 Effect of carbon fiber* content on strength at 14 days for Mortar B

1. Without chemical agents

Fiber content (% of weight of cement)	Strength (MPa) Flexural	Compressive
/	4.80 (± 2.3%)	26.02 (± 2%)
0.5	5.28 (± 7.6%)	30.70 (± 3%)
1.0	6.41 (± 5.3%)	31.84 (± 5.2%)
2.0	6.45 (± 8.9%)	29.23 (± 8%)

2. With chemical agents

Fiber content (% of weight of cement)	Strength (MPa) Flexural	Compressive
/	5.95 (± 1.0%)	32.84 (± 6%)
0.5	6.37 (± 7.6%)	31.63 (± 5%)
1.0	6.92 (± 3.7%)	34.11 (± 4%)
2.0	7.03 (± 9.7%)	25.88 (± 4.7%)

* 3.0 mm long carbon fibers.

Conclusion: The optimum fiber content is 1% of weight of cement.

Table 13 Effect of sodium sulfate on slump and flexural strength at 3 days of curing for Mortar B*

Sodium sulfate/cement	Slump (cm)+	Flexural strength (MPa)
0.5%	7.7	5.88 (± 5.8%)
0.4%	7.7	5.81 (± 3.2%)
0.3%	11	5.75 (± 2.4%)
0.2%	13.5	5.48 (± 4.7%)
0	18	5.71 (± 5.8%)

*Mix design as in Table 7 except water/cement = 0.35, Aggregate B/cement = 1.5, and sodium sulfate/cement ratio was varied from 0 to 0.5%.

+Mold for slump test: cylinder, D_0 = 7.7 cm, H_0 = 5.8 cm. The slump was determined by measuring the outer surface of the horizontal displaced mortar.

Table 14 Raw materials for Concrete D with low fluidity

Water/cement = 0.45

Cement : Aggregate B : Aggregate D = 1 : 1.5 : 2.49 (by weight)

Fibers/cement = 0.5%, 5.1 mm long

Methylcellulose/cement = 0.8%

Colloids 1010: 0.13 vol.% (if applicable)

Silica fume B: 15% replacement of cement

Water reducing agent (TAMOL SN)/cement = 0.7%

Accelerating agents:

- Triethanolamine/cement = 0.06%
- Potassium aluminum sulfate/cement = 0.5%
- Sodium sulfate/cement = 0.3%

Air entrainer/cement = 3% (if applicable)

Note: The raw materials were the same for Concrete C except that Aggregate C was used instead of Aggregate D.

M = Methylcellulose
Chem = chemical agents, consisting of water reducing agent and accelerating agents.
1010 = Colloids 1010

Table 15 Effect of chemical agents and silica fume B on flexural strength for Concrete D with low fluidity

	Flexural strength (MPa)		
	28 days	14 days	7 days
(1) Plain	4.76 (± 4.5%)	4.39 (± 6.0%)	3.40 (± 2.1%)
(2) + Chem	7.29 (± 6.0%)	5.14 (± 4.0%)	4.76 (± 5.0%)
(3) + silica fume B	7.40 (± 9.6%)	6.31 (± 2.2%)	4.40 (± 9.7%)
(4) + Chem + silica fume B	7.52 (± 2.7%)	6.54 (± 15%)	5.70 (± 4.6%)

Table 16 Effect of carbon fibers, methylcellulose and Colloids 1010 on flexural strength for Concrete D with low fluidity.

	Flexural strength (MPa)		
	28 days	14 days	7 days
(1) [a]Fibers + Chem	7.46 (± 9.0%)	6.71 (± 9.6%)	5.62 (± 8.7%)
(2) [b]Fibers + Chem	/	6.42 (± 11%)	5.46 (± 9.2%)
(3) [b]Fibers + Chem + M	7.83 (± 4.5%)	6.69 (± 5.6%)	6.56 (± 6.4%)
(4) [b]Fibers + Chem + M + silica fume	8.07 (± 2.7%)	6.84 (± 3.2%)	6.66 (± 2.3%)
(5) [b]Fibers + Chem + M + 1010	/	7.86 (± 7%)	6.96 (± 5%)

[a]Dry Mix
[b]Wet Mix

Table 17 Freeze-thaw durability test for Concrete D with low fluidity

	Flexural strength (MPa)	
	37 days	7 days, then 30 cycles at 1 cycle/day
Plain Concrete D	6.64 (± 7%)	4.87 (± 3%)
+ Fibers + M* + Chem + silica fume B	8.84 (± 3%)	7.52 (± 4.6%)

Note: M = methylcellulose

Table 18 Effect of silica fume A vs silica fume B on the flexural strength at 3 days for Mortar A*

	Flexural strength (MPa)
(1) Plain + silica fume A	4.68 (± 2.0%)
(2) Plain + silica fume B	4.09 (± 3.0%)
(3) Fibers + M + silica fume A	6.42 (± 5.0%)
(4) Fibers + M + silica fume B	5.26 (± 5.0%)

*Raw Materials:

Water/cement = 0.45

Aggregate A/cement = 1.5

TAMOL SN/cement = 2%

Methycellulose/cement = 0.4%

Silica fume A/cement = 0.15

Silica fume B/cement = 0.15

Fibers/cement = 1.0%; 5.1 mm long

Note:

M = Methylcellulose

Table 19 Comparison of properties of silica fume A and silica fume B

	Silica Fume A	Silica Fume B
Manufacturer	Elkem Materials Inc. (EMS 960)	Tam Ceramics
Particle size	100% < 1 mm 0.15 μm (Ave.) Range 0.03 μm-0.5 μm 20% 0.04 μm	> 10 μm 19% > 1 μm 44% > 0.3 μm 76%
Bulk density (g/cm^3)	0.16 - 0.45	0.48
Specific gravity	2.2	2.3
SiO_2	94%	90.2%
Surface area	22 m^2/g (spherical)	12.5 m^2/g (spherical)
Mohs hardness	6.5	/
Color	Grey	Light grey
Chemical Composition	C 3% FeO 0.1% Al_2O_3 0.36% CaO 0.27% MgO 0.2% 3.6% Ion on ignition NaO, KO < 0.5%	Much less C ZrO_2

Table 20 Raw materials for Mortar A

Water/cement = 0.45

Aggregate A/cement = 1.5

Fibers/cement = 0.5%, 5.1 mm long

Methylcellulose/cement = 0.4%

Silica fume A/cement = 0.15

Colloids 1010: 0.13 vol.%

Water reducing agent (TAMOL SN)/cement = 2%

Accelerating agents:

- Triethanolamine/cement = 0.06%
- Potassium aluminum sulfate/cement = 0.5%
- Sodium sulfate/cement = 0.5%

Note: Dis = dispersant, consisting of methylcellulose and Colloids 1010

Chem = chemical agents, consisting of water reducing agent and accelerating agents

Table 21 Flexural strength (MPa) of Mortar A at different curing ages

		14 days	7 days
1.	Plain Mortar A	4.75 (± 5%)	3.36 (± 4%)
2.	+ fibers + Dis	7.61 (± 5%)	6.87 (± 8%)
3.	+ Chem + silica fume A	7.60 (± 4%)	5.11 (± 3%)
4.	+ fibers + Dis + Chem + silica fume A	9.81 (± 7%)	7.68 (± 5%)

Table 22 Flexural toughness (MPa.cm) of Mortar A at different curing ages

		14 days	7 days
1.	Plain Mortar A	0.036 (± 5%)	0.020 (± 4%)
2.	+ fibers + Dis	0.192 (± 5%)	0.058 (± 8%)
3.	+ Chem + silica fume A	0.081 (± 4%)	0.056 (± 3%)
4.	+ fibers + Dis + Chem + silica fume A	0.176 (± 7%)	0.046 (± 5%)

Table 23 Raw materials for Concrete D with normal fluidity

Water/cement = 0.50

Cement : Aggregate B : Aggregate D = 1 : 1.5 : 2.49 (by weight)

Fibers/cement = 0.5%, 5.1 mm long

Methylcellulose/cement = 0.4%

Silica fume A/cement = 0.15

Colloids 1010: 0.13 vol.%

Water reducing agent (TAMOL SN)/cement = 2%

Accelerating agents:

- Triethanolamine/cement = 0.06%
- Potassium aluminum sulfate/cement = 0.5%
- Sodium sulfate/cement = 0.5%

Note: Dis = dispersant, consisting of methylcellulose and Colloids 1010

Chem = chemical agents, consisting of water reducing agent and accelerating agents

Table 24 Flexural strength (MPa) of Concrete D (with normal fluidity) at different curing ages

	28 days	14 days	7 days
1. Plain Concrete D	5.00 (± 5%)	4.22 (± 4%)	3.10 (± 4%)
2. + fibers + Dis	7.95 (± 6%)	6.65 (± 3%)	4.84 (± 2%)
3. + Chem + silica fume A	7.86 (± 3%)	5.89 (± 2%)	5.03 (± 4%)
4. + fibers + Dis + Chem	/	7.15 (± 7%)	5.22 (± 6%)
5. + fibers + Dis + Chem + silica fume A	9.23 (± 9%)	7.74 (± 9%)	5.90 (± 7%)

Table 25 Flexural toughness (MPa.cm) of Concrete D (with normal fluidity) at different curing ages

	28 days	14 days	7 days
1. Plain Concrete D	0.083 (± 5%)	0.077 (± 4%)	0.047 (± 4%)
2. + fibers + Dis	0.221 (± 6%)	0.210 (± 3%)	0.123 (± 2%)
3. + Chem + silica fume A	0.187 (± 3%)	0.095 (± 2%)	0.107 (± 4%)
4. + fibers + Dis + Chem + silica fume A	0.253 (± 9%)	0.198 (± 9%)	0.085 (± 7%)

Table 26 Compressive strength (MPa) of Concrete D of normal fluidity at different curring ages.

		90 days	7 days
1.	Plain Concrete D	30.35 (± 3%)	27.23 (± 4%)
2.	+ fibers + Dis	25.48 (± 6%)	23.39 (± 9%)
3.	+ Chem + silica fume A	56.67 (± 5%)	35.09 (± 3%)
4.	+ fibers + Dis + Chem + silica fume A	36.90 (± 8%)	26.90 (± 8%)

Table 27 Freeze-thaw durability test of Concrete D with normal fluidity

	Flexural strength (MPa)	
	44 days	14 days, then 30 cycles at 1 cycle/day
1. Plain Concrete D	5.28 (± 2.3%)	4.65 (± 2%)
2. + fibers + Dis	8.10 (± 7%)	7.54 (± 6%)
3. + Chem + silica fume A	8.14 (± 4%)	7.33 (± 5.4%)
4. + fibers + Dis + Chem + silica fume A	9.70 (± 8%)	9.21 (± 9%)

Table 28 Flexural strength of air-entrained Concrete D of normal fluidity*

	Flexural strength (MPa)		
	28 days	14 days	7 days
1. Air-entrained Concrete D	5.04 (± 8%)	4.04 (± 6%)	3.84 (± 9%)
2. + fibers + Dis	5.84 (± 3%)	5.33 (± 8%)	4.42 (± 9%)
3. + Chem + silica fume A	7.42 (± 10%)	7.24 (± 9%)	6.05 (± 8%)
4. + fibers + Dis + Chem + silica fume A	9.00 (± 5%)	7.86 (± 10%)	7.03 (± 9%)

*Raw materials as described in Table 23, except that water/cement = 0.45 and air-entrainer/cement = 1%.

Table 29 Flexural toughness of air-entrained Concrete D of normal fluidity*

	Flexural toughness (MPa.cm)		
	28 days	14 days	7 days
1. Air-entrained Concrete D	0.179 (± 8%)	0.185 (± 6%)	0.141 (± 9%)
2. + fibers + Dis	0.189 (± 3%)	0.278 (± 8%)	0.206 (± 9%)
3. + Chem + silica fume A	0.199 (± 10%)	0.154 (± 9%)	0.215 (± 8%)
4. + fibers + Dis + Chem + silica fume A	0.274 (± 5%)	0.265 (± 10%)	0.210 (± 9%)

*Raw materials as described in Table 23, except that water/cement = 0.45 and air-entrainer/cement = 1%.

Table 30 Flexural strength (MPa) of Concrete C* at different curing ages

	14 days	7 days
1. Plain Concrete C	4.15 (± 3%)	3.32 (± 3%)
2. + fibers + Dis	6.39 (± 5%)	4.94 (± 5%)
3. + Chem + silica fume A	6.12 (± 3%)	4.96 (± 4%)
4. + fibers + Dis + Chem + silica fume A	7.18 (± 8%)	6.64 (± 7%)

*Same as Concrete D with normal fluidity except using Aggregate C instead of Aggregate D.

Table 31 Flexural toughness (MPa.cm) of Concrete C* at different curing ages

	14 days	7 days
1. Plain Concrete C	0.052 (± 3%)	0.048 (± 3%)
2. + fibers + Dis	0.104 (± 5%)	0.098 (± 5%)
3. + Chem + silica fume A	0.087 (± 3%)	0.093 (± 4%)
4. + fibers + Dis + Chem + silica fume A	0.156 (± 8%)	0.124 (± 7%)

*Same as Concrete D with normal fluidity except using Aggregate C instead of Aggregate D.

Table 32 Effect of the water/cement ratio (W/C) on the flexural strength and slump of "Concrete D of normal fluidity".

			Flexural strength (MPa)		Slump (in)	
Material	W/C	28 days	14 days	7 days	Without air-entrainer	With air-entrainer
1. Plain	0.50	5.00(±5%)	4.22(±4%)	3.10(±4%)	6	/
	0.45	/	5.25(±9%)	4.01(±8%)	5	6
	0.40	/	6.05(±8%)	5.38(±7%)	4	/
2. +fibers +Dis	0.50	7.95(±6%)	6.65(±3%)	4.84(±2%)	4	/
	0.45	/	6.91(±5%)	5.59(±8%)	2	3
	0.40	/	7.13(±8%)	6.02(±3%)	1.8	/
3. +Chem +silica fume A	0.50	7.86(±3%)	5.89(±2%)	5.03(±4%)	4	/
	0.45	/	9.97(±1%)	/	3	4
	0.40	/	12.82(±3%)	/	1	/
4. +fibers+Dis +Chem +silica fume A	0.50	9.23(±9%)	7.74(±9%)	5.90(±7%)	4	/
	0.45	/	11.82(±5%)	/	1	2
	0.40	/	/	/	/	/

Table 33 Air content of Concrete D of normal fluidity

	Air content (%)	
	Without air-entrainer*	With air-entrainer+
1. Plain Concrete D	1	6
2. + fibers + Dis	7	10
3. + Chem + silica fume A	3	7
4. + fibers + Dis + Chem + silica fume A	6	9

*Water/cement = 0.50
+Water/cement = 0.45

Table 34 Volume fraction of fibers in mortars and concretes with fibers in the amount of 0.5% of the weight of the cement.

	Vol. fraction fibers
Concrete C or D	0.189%
Mortar B	0.094%
Mortar A	0.244%

Table 35 Effectiveness of fibers + Dis + Chem + silica fume A (Wet Mix) in increasing the flexural strength and flexural toughness

	Increase due to fibers + Dis + Chem + microsilica		
	28 days	14 days	7 days
Flexural strength			
*Concrete D with normal fluidity			
Without air-entrainment	85%	83%	90%
With air-entrainment	79%	95%	83%
*Concrete C (without air-entrainment)		73%	100%
+ Mortar A (without air-entrainment)		110%	130%
Flexural toughness			
*Concrete D with normal fluidity			
Without air-entrainment	205%	160%	80%
With air-entrainment	53%	43%	49%
*Concrete C (without air-entrainment)		200%	160%
+Mortar A (without air-entrainment)		390%	132%

* 0.189 vol.% fibers

+ 0.244 vol.% fibers

Table 36 Effectiveness of fibers + Dis (Wet Mix) in increasing the flexural strength and flexural toughness

	Increase due to fibers + Dis (Wet Mix)		
	28 days	14 days	7 days
Flexural strength			
*Concrete D with normal fluidity			
Without air-entrainment	59%	58%	56%
With air-entrainment	16%	32%	15%
*Concrete C (without air-entrainment)		54%	49%
+Mortar A (without air-entrainment)		60%	100%
Flexural toughness			
*Concrete D with normal fluidity			
Without air-entrainment	170%	170%	160%
With air-entrainment	6%	50%	46%
*Concrete C (without air-entrainment)		100%	100%
+Mortar A (without air-entrainment)		430%	190%

*0.189 vol.% fibers
+0.244 vol.% fibers

Table 37 Effectiveness of fibers + Chem (Dry Mix) in increasing the flexural strength

	Increase due to fibers + Chem (Dry Mix)		
	28 days	14 days	7 days
+Mortar B	21%	33%	37%
*Concrete D with low fluidity	57%	53%	65%

+0.094 vol.% fibers
*0.189 vol.% fibers

Table 38 Electrical resistivity (Ω.cm) of Concrete D with normal fluidity and Mortar A

	Concrete D	Concrete A
1. Plain	1.36×10^7	1.46×10^5
2. With fibers + M	3.70×10^6	2.53×10^4
3. With Chem + silica fume A	1.19×10^7	9.53×10^4
4. With fibers + M + Chem + silica fume A	2.32×10^6	2.31×10^4

Note: M = methylcellulose

Table 39 Price increase per cubic yard

		Mortar A, Concretes C and D	Mortar B
1.	Plain	/	/
2.	+ fibers*	17.5%	15.4%
3.	+ Chem	7%	6%
4.	+ M	5%	5%
5.	+ 1010	0.25%	0.25%
6.	+ silica fume A	9%	9%
7	+ fibers* + Chem	24.5%	21.4%
8.	+ fibers* + M + 1010	22.75%	20.65%
9.	+ Chem + silica fume A	16%	15%
10.	+ fibers* + M + 1010 + Chem + silica fume A	38.75%	35.65%
11.	+ fibers**	35%	30.8%
12.	+ fibers** + Chem	42%	36.8%
13.	+ fibers** + M + 1010	40.25%	36.05%
14.	+ fibers** + M + 1010 + Chem + silica fume A	56.25%	51.05%

* fibers, 0.5% of weight of cement
** fibers, 1% of weight of cement

Note:
M = methylcellulose
1010 = Colloids 1010

Table 40 Properties (at 28 days of curing) and price relative to those of plain Concrete D.

	Increase	
	Concrete 1*	Concrete 2+
Flexural strength	85%	57%
Flexural toughness	205%	125%
Price	39%	16%

*Concrete of best performance [i.e., Concrete D with fibers (0.5% of weight of cement) + Dis + Chem + silica fume A]

+Competitive concrete [i.e., Concrete D with Chem + silica fume A]

Table 41 Properties (at 28 days of curing) and price of Concrete 1* relative to those of Concrete 2*

	Increase
Flexural strength	18%
Flexural toughness	35%
Price	20%

*See Table 40 for definitions of Concrete 1 and Concrete 2.