

# Microstructural and Mechanical Effects of Latex, Methylcellulose, and Silica Fume on Carbon Fiber Reinforced Cement



by Pu-Woei Chen, Xuli Fu, and D. D. L. Chung

*The effect of methylcellulose, silica fume, and latex on the degree of dispersion of short carbon fibers in cement paste (with water-reducing agent in an amount varying from 0 to 3 percent by weight of cement) was assessed. This degree, as indicated by the ratio of the measured volume of electrical conductivity to the calculated value, and the effectiveness of the fibers in enhancing the tensile/flexural properties attained by using methylcellulose and silica fume were higher than those attained by using methylcellulose alone or latex. Methylcellulose was superior to latex in giving a high degree of fiber dispersion at fiber volume fractions < 1 percent, as measured by this technique, but latex resulted in superior tensile-flexural properties and lower content and size of air voids than methylcellulose. With the fiber content fixed at 0.53 vol. percent, the degree of fiber dispersion, as measured by this technique, decreased with increasing latex-cement ratio from 0.05 to 0.30, while the void content attained a minimum at an intermediate latex-cement ratio of 0.15. As a result of the former, the flexural toughness decreased monotonically with increasing latex-cement ratio. As a result of the latter, the flexural strength attained a maximum at an intermediate latex-cement ratio of 0.15. In contrast, both flexural toughness and strength increased monotonically with increasing latex-cement ratio when fibers were absent.*

**Keywords:** carbon; cements; concretes; flexural strength; latex (plastic); silica fume; voids.

## INTRODUCTION

The use of short fibers to reinforce concrete is receiving increasing attention due to the increase in tensile/flexural toughness and, in some cases, increase in the tensile/flexural strength and decrease in the drying shrinkage as well.<sup>1</sup> In contrast to continuous fibers, short fibers can be added to the concrete mix due to their discontinuous nature. Furthermore, short fibers are much less expensive than continuous fibers. However, the effectiveness of the short fibers depends greatly on the degree of fiber dispersion in the mix. A high degree of fiber dispersion allows the property improvements to be attained at a small fiber content, thus saving material and processing costs (as a high fiber content requires the use of special mixers) and avoiding excessive compressive strength decrease (due to the increase in air void content as the fiber content increases).

In spite of the obvious importance of the degree of fiber dispersion, no quantitative assessment has been made previously. This is because 1) the use of microscopy to assess the degree of fiber dispersion is tedious, difficult, and ineffective, and 2) mechanical properties alone, being sensitive to the void content and fiber-matrix bonding, as well as the degree of dispersion, do not provide a good indication of the degree of fiber dispersion. In this work, by using electrically conducting short fibers (i.e., carbon fibers) and noting that the electrical conductivity (reciprocal of the volume electrical resistivity) of the cement paste, mortar, or concrete is governed by the degree of fiber dispersion and is negligibly affected by the voids (which are low in volume fraction) or by the intrinsic conductivity of admixtures, such as silica fume and latex, which are all poor in electrical conductivity compared to carbon fibers, we have been able to provide a quantitative assessment of the degree of fiber dispersion.

Various ingredients, such as methylcellulose,<sup>2,3</sup> silica fume,<sup>2-5</sup> and latex,<sup>6-12</sup> have been added to cement paste, mortar, or concrete to help the fiber dispersion, although these ingredients also serve other functions. Due to the lack of quantitative assessment of the degree of fiber dispersion, the relative effectiveness of these ingredients for fiber dispersion has not been previously assessed. At a fixed fiber content of 0.5 percent by weight of cement, the flexural strength of mortar increases in the following order among the ingredients used: 1) methylcellulose, 2) methylcellulose + silica fume, and 3) latex.<sup>3,11</sup> However, this does not imply that the degree of fiber dispersion also increases in this order. In this work, through electrical conductivity measurement, quantitative comparison was made of the effect of these ingredients on the degree of fiber dispersion.

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The addition of latex to concrete without fiber is conducted due to the resulting increase in flexural strength, compressive strength, toughness, and permeation resistance.<sup>6-10</sup> The addition of latex to fiber reinforced concrete<sup>11-13</sup> is similarly beneficial, causing increases in tensile, compressive, and flexural strengths as well as flexural toughness whether the fibers are carbon, polyethylene, or steel.<sup>13</sup> Although the positive effect of latex addition on the mechanical properties of fiber reinforced concrete has been previously reported, the dependence on the latex-cement ratio of the mechanical properties, the void content, and the degree of fiber dispersion has not been previously reported for any fiber type. A systematic study correlating all these quantities is needed to understand the microstructural and mechanical effects of the latex.

## RESEARCH SIGNIFICANCE

This work provides a comparative assessment of the degree of dispersion of short carbon fibers in cement pastes with latex, methylcellulose, or methylcellulose + silica fume, together with a water-reducing agent in an amount varying

**Table 1—Properties of carbon fibers**

Filament diameter	10 $\mu$ m
Tensile strength	690 MPa
Tensile modulus	48 GPa
Elongation at break	1.4 percent
Electrical resistivity	$3.0 \times 10^{-3} \Omega \cdot \text{cm}$
Specific gravity	1.6 g cm <sup>-3</sup>
Carbon content	98 wt. percent

**Table 2—Mix proportions of cement pastes used for comparing effects of latex, methylcellulose, and silica fume**

Fiber vol., percent	Water-cement ratio			WR/cement, percent			Slump, mm		
	With L	With M	With M + SF	With L	With M	With M + SF	With L	With M	With M + SF
0	0.23	0.32	0.35	0	0.5	3	160	150	130
0.53	0.23	0.32	0.35	0	1	3	157	130	125
1.06	0.23	0.32	0.35	1	3	3	160	140	120
2.12	0.23	0.33	0.35	2	3	3	140	130	110
3.18	0.25	0.36	0.37	2.5	3	3	130	110	100
4.24	0.27	0.40	0.40	3	3	3	110	77	77

Note: L = latex; M = methylcellulose; SF = silica fume; WR = water reducing agent.

from 0 to 3 percent by weight of cement. In addition, it provides a systematic study correlating the microstructural effects (degree of fiber dispersion and void content) and the mechanical effects (flexural toughness and flexural strength) of latex in cement paste containing short carbon fibers. Moreover, this work provides optimum values of the latex-cement ratio for attaining high flexural toughness and high flexural strength in cement paste containing carbon fibers. These findings, though obtained for the case of carbon fibers, may apply to other types of fibers as well.

## EXPERIMENTAL METHODS

### Raw materials

The short carbon fibers were isotropic-pitch-based and un-sized. The nominal fiber length and monofilament diameter were 5 mm and 10  $\mu$ m, respectively. The fiber properties are shown in Table 1. No aggregate, whether fine or coarse, was used. Table 2 describes the mix proportions of the three types of cement pastes tested as a function of carbon fiber volume fraction for the purpose of comparing the effects of latex, methylcellulose, and silica fume. They were 1) cement paste with latex, 2) cement paste with methylcellulose (M), and 3) cement paste with methylcellulose (M) and silica fume (SF). Both the water-cement ratio and the water-reducing agent (WR)-cement ratio were chosen to increase with increasing fiber volume fraction to maintain the slump mostly in the range from 100 to 160 mm (Table 2). In spite of these choices of the two ratios, the slump decreased with increasing fiber volume fraction, particularly for fiber contents beyond 4 vol. percent. The required water-cement ratio and the water-reducing agent-cement ratio varied with the ingredient used. Among the three formulations, the use of latex required the least values of both ratios; the use of methylcellulose plus silica fume required the largest values of both ratios. In each category in Table 2, additions of L, M, or M + SF were used whether fibers were present or not to obtain the effect of the fiber addition alone.

The water-reducing agent powder used contained 93 to 96 percent sodium salt of a condensed naphthalene sulfonic acid. The latex was a styrene-butadiene copolymer latex, a dispersion made by emulsion polymerization; it was used in the amount of 0.20 of the weight of the cement in the study of the effect of the fiber volume fraction, and in the amount of 0.05 to 0.30 of the weight of the cement in the study of the effect of latex content at a fixed fiber content of 0.53 vol. percent (or 0.5 percent by weight of cement). The antifoam

(silica fume) used was in the amount of 0.5 percent of the weight of the latex; it was used whenever latex was used. Methylcellulose in the amount of 0.4 percent of the cement weight was used. The defoamer used along with it was in the amount of 0.13 vol. percent; it was used whenever methylcellulose was used. The silica fume was used in the amount of 0.15 of the weight of the cement.

### Mixing and curing procedures

A mixer with a flat beater was used. For the case of cement paste containing latex, the latex, antifoam, and carbon fibers first were mixed by hand for about 1 min. Then this mixture, cement, water, and the water-reducing agent were mixed for 5 min. In the case of cement paste containing methylcellulose, methylcellulose was dissolved in water and then fibers and the defoamer were added and stirred by hand for about 2 min. Then this mixture, cement, water, and the water-reducing agent (and silica fume, if applicable) were mixed for 5 min.

After pouring the mix into oiled molds, an external vibrator was used to decrease the amount of air bubbles. The specimens were demolded after 1 day and then allowed to cure at room temperature in air (30 percent relative humidity) for either 7 or 28 days.

### Testing procedure

The slump test was performed on a 77-mm-diameter and 58-mm-high plastic cylinder. The slump was determined by measuring the outer surface of the horizontal displaced mortar.

Tensile testing was performed on dogbone-shaped specimens. The specimen cross section was 30 x 20 mm in the narrow part of the dogbone shape. Six specimens of each type were used. The screw-action mechanical testing system was used at a crosshead speed of 1.27 mm/min. The strain was measured by using a strain gage attached to the narrow part of the dogbone-shaped specimen. The strain allowed determination of the tensile modulus and ductility.

Flexural testing was performed by three-point bending (ASTM C348-80) with a span of 140 mm. The specimen size was 160 x 40 x 40 mm. Six specimens of each type were used. The hydraulic Material Testing System (MTS) was used for flexural testing with a crosshead speed of 1.27 mm/min and the load-deflection curve was automatically recorded. The deflection was based on the crosshead travel. The flexural toughness was calculated from the area under the flexural stress/displacement curve obtained in flexural testing.

Volume electrical resistivity was measured by the four-probe method (outer two probes for passing current and inner two probes for voltage measurement), using silver paint for the four electrical contacts, which were applied around the perimeter of the specimen (160 x 40 x 40 mm) in four parallel planes perpendicular to the current direction (which is along the longest dimension of the specimen). The DC current used ranged from 0.1 to 4.0 A. Six specimens of each type were tested. In a separate experiment, resistivity was measured on specimens of different cross-sectional areas and it was found that resistivity was independent of the cross-sectional area. This independence means that surface conduction did not contribute to the volume resistivity result.

Scanning electron microscopy (SEM) was used to examine the fracture surfaces after flexural testing for the purpose of determining air void content (volume fraction) and size. In addition, air content was measured using ASTM C 185-91a.

## RESULTS AND DISCUSSION

In all tables and figures, "plain" refers to the cement paste that contained no fiber, methylcellulose (M), silica fume (SF), latex (L), or water-reducing agent.

Table 3 and Fig. 1 show the effect of L, M, and M + SF on tensile strength, modulus, and ductility (strain at failure) at 7 days of curing. Strength was significantly increased by fiber addition, especially in the cases of M + SF and M. The modulus was decreased by fiber addition in the case of M + SF but was not much affected by fiber addition in the cases of M

**Table 3—Tensile properties of cement pastes with various volume fractions of carbon fibers**

Sample	With L			With M			With M + SF		
	Strength, MPa (percent)	Modulus, GPa (percent)	Ductility, percent (percent)	Strength, MPa (percent)	Modulus, GPa (percent)	Ductility, percent (percent)	Strength, MPa (percent)	Modulus, GPa (percent)	Ductility, percent (percent)
Plain mortar	0.88 (±4.7)	10.9 (±3.0)	0.004 (±1.0)	0.88 (±4.7)	10.9 (±3.0)	0.004 (±1.0)	0.88 (±4.7)	10.9 (±3.0)	0.004 (±1.0)
(+L)/(+M)/ (+M+SF)	3.03 (±4.5)	11.5 (±2.1)	0.0352 (±1.2)	1.37 (±2.3)	6.6 (±2.1)	0.0209 (±0.9)	0.83 (±5.2)	40 (±1.2)	0.0088 (±1.1)
+0.53 vol. percent	3.15 (±2.4)	7.3 (±1.8)	0.0413 (±0.8)	1.95 (±5.6)	10 (±1.1)	0.0192 (±1.5)	1.88 (±6.1)	14 (±3.4)	0.0173 (±1.2)
+1.06 vol. percent	3.16 (±3.5)	6.14 (±2.1)	0.0402 (±1.5)	2.61 (±4.2)	11.2 (±1.5)	0.0197 (±1.2)	2.03 (±3.5)	17.3 (±2.6)	0.0192 (±2.3)
+2.12 vol. percent	3.65 (±4.3)	13.2 (±2.4)	0.0407 (±0.6)	3.05 (±4.1)	12.4 (±1.2)	0.0203 (±0.7)	2.84 (±4.3)	10.7 (±2.7)	0.0404 (±1.7)
+3.18 vol. percent	3.32 (±5.1)	17.5 (±2.3)	0.0427 (±0.6)	2.97 (±3.7)	5.4 (±0.9)	0.0503 (±1.1)	3.01 (±5.7)	8.1 (±3.5)	0.0406 (±5.6)
+4.24 vol. percent	2.92 (±3.2)	5.4 (±1.9)	0.0436 (±0.8)	2.65 (±5.1)	6.1 (±2.3)	0.185 (±0.1)	2.49 (±4.2)	5.1 (±4.3)	0.113 (±2.1)

Note: L = latex; M = methylcellulose; SF = silica fume; F = fibers.

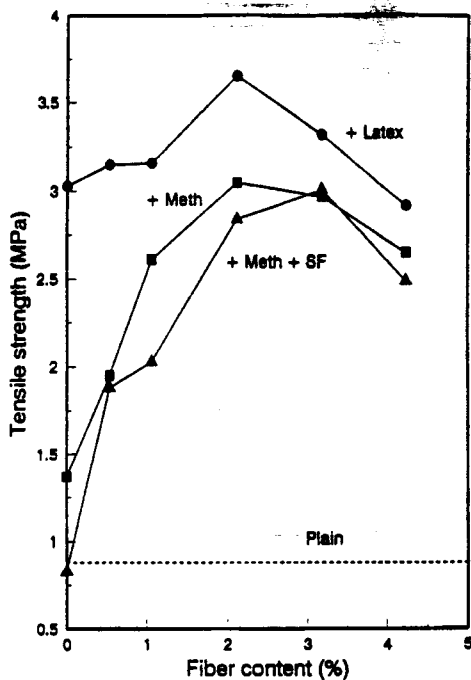


Fig. 1—Dependence of tensile strength on fiber content of cement pastes

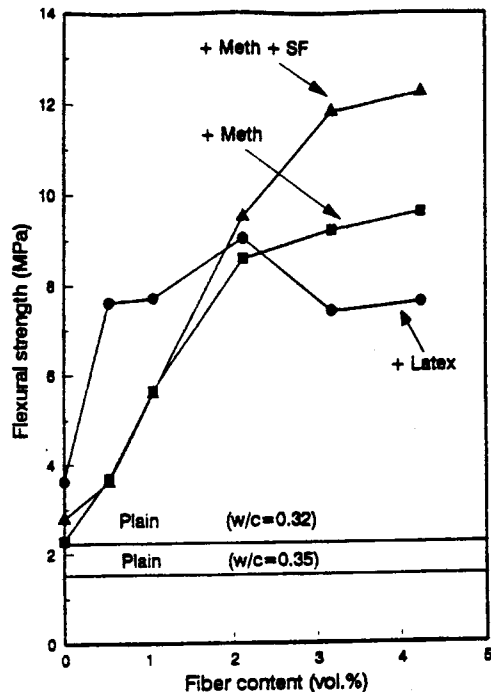


Fig. 2—Dependence of flexural strength content on fiber content

Table 4—Fractional increase of tensile strength due to fibers alone for cement pastes\*

Fiber volume fraction, percent	With L	With M	With M + SF
0.53	0.040	0.42	1.27
1.06	0.043	0.91	1.45
2.12	0.205	1.23	2.42
3.18	0.096	1.17	2.63
4.24	-0.036	0.93	2.00

\* Increase is relative to case without fibers but with corresponding dispersant. Note: L = latex; M = methylcellulose; SF = silica fume.

Table 5—Fractional increase in flexural strength due to fibers alone\*

Fiber volume fraction, percent	With L	With M	With M + SF
0.53	1.10	0.61	0.29
1.06	1.13	1.47	1.01
2.12	1.49	2.75	2.41
3.18	1.05	3.02	3.24
4.24	1.10	3.19	3.38

\* Increase is relative to case without fibers but with corresponding dispersant. Note: L = latex; M = methylcellulose; SF = silica fume.

sile ductility due to the fiber addition resulted from toughening via the fiber pullout mechanism. The increased tensile strength due to the fiber addition indicates that the fiber-matrix bonding was substantial. The drop in the tensile strength at high fiber volume fractions is attributed to air voids (as shown by SEM) resulting from the decreased workability of the mix.

The formulations with latex gave higher tensile strength and ductility than those with either M or M + SF when the fiber volume fraction was  $\leq 2.1$  percent. This is because of the inherently high strength and ductility of the cement paste with latex, even in the absence of fibers.

Table 4 gives the fractional increase of the tensile strength (at 7 days of curing) due to the fibers alone, i.e., the fractional increase relative to the cement paste without fibers but with the corresponding dispersant (L, M, or M + SF). The fractional increase was highest for the case of M + SF and lowest for the case of latex at all fiber volume fractions.

Flexural testing is a standard ASTM test for concretes or mortars, though tensile testing is in this case considered to be scientifically more meaningful. Therefore, flexural testing was performed. Fig. 2 shows the effect of L, M, and M + SF on the flexural strength for cement paste containing various volume fractions of carbon fibers (0 to 4.2 vol. percent) at 7 days of curing. Due to the fact that the difficulty of fiber dispersion increased with increasing fiber content, the highest flexural strength was obtained at an intermediate fiber content of 2.1 vol. percent for mortar containing latex. Latex gave the highest flexural strength for fiber contents below 2 vol. percent; M + SF gave the highest flexural strength for fiber contents above 2 vol. percent.

Both the air void content (Fig. 3) and the average air void size (Fig. 4), as determined by SEM at 7 days of curing, in

and L. Ductility was more significantly increased by fiber addition in the case of M + SF than in the other two cases. The ductility monotonically increased with the fiber volume fraction, whereas the strength first increased and then decreased with the fiber volume fraction (Table 3).

That the tensile modulus was not much increased, if at all, by fiber addition is expected from the low volume fraction of fibers (5.4.2 percent). It is postulated that the increased ten-

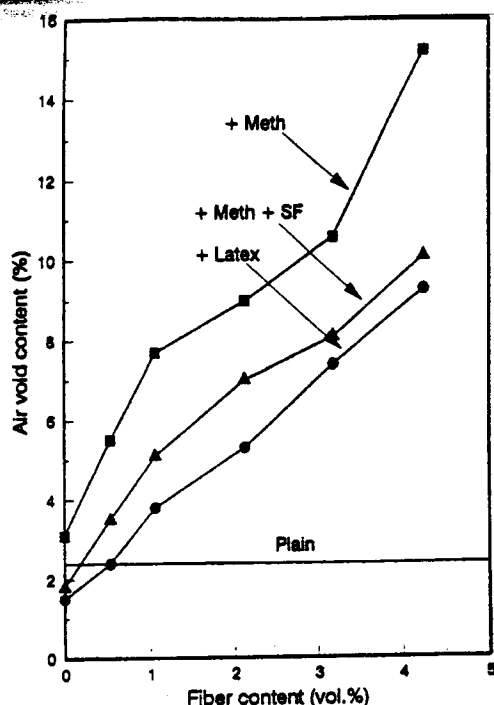


Fig. 3—Dependence of air void content on fiber content

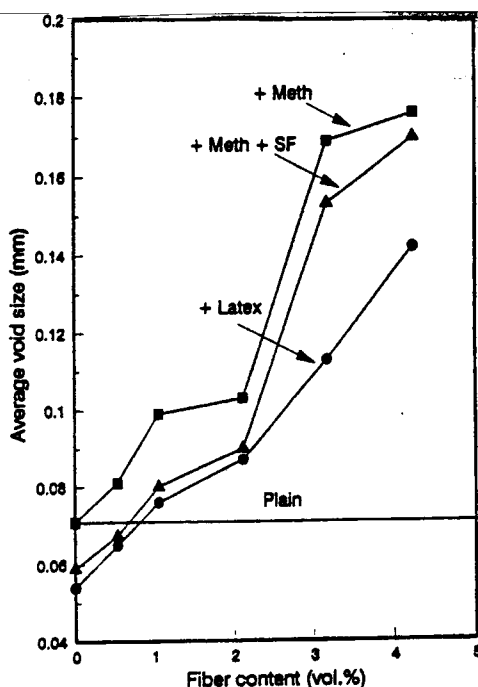


Fig. 4—Dependence of average air void size on fiber content

creased with increasing fiber content. At the same fiber content, different dispersants resulted in different air void contents and different average air void sizes, and caused the fibers to be effective for increasing the flexural strength to different degrees. Among the three dispersants, latex gave the lowest air void content and size, whereas methylcellulose gave the highest air void content and size. Table 5 shows the fractional increase in the flexural strength (at 7 days of curing) due to the fibers alone. The fractional increase is higher for M + SF than either M or L for fiber volume fractions greater than 3 percent. At fiber volume fractions less than 1 percent, L gave the highest fractional increase; M gave higher fractional increase than L at fiber volume fractions greater than 1 percent.

Fig. 5 shows the effect of L, M, and M + SF on the flexural toughness (at 7 days of curing) of cement paste containing various volume fractions of carbon fibers. At the same fiber content, different dispersants caused the fibers to be effective for increasing the flexural toughness to different degrees. The flexural toughness increased monotonically with increasing fiber content in all cases. The highest flexural toughness (12.3 MPa.mm) was attained by the use of M + SF. The toughness exhibits trends that are consistent with the tensile ductility (Table 3).

Table 6 shows the volume electrical resistivity of various cement pastes at 7 days of curing. At a given fiber volume fraction, L yielded higher resistivity than either M or M + SF, whether fibers were present or not. When fibers were absent, M yielded the lowest resistivity and L yielded the highest resistivity. However, the difference was small, in spite of the fact that latex, a polymer, had an intrinsically higher resistivity than the cementitious and ceramic materials. That the difference was small when fibers were absent supports

Table 6—Volume electrical resistivity of various types of cement paste

Samples	Volume electrical resistivity ( $\Omega \cdot \text{cm}$ )		
	With L	With M	With M + SF
Plain	$1.50 \times 10^5$	$1.50 \times 10^5$	$1.50 \times 10^5$
(+L)/(+M)/(+M+SF)	$2.75 \times 10^5$	$1.49 \times 10^5$	$2.32 \times 10^5$
+0.53 vol. percent fibers	$9.87 \times 10^4$	$2.53 \times 10^4$	$2.14 \times 10^3$
+1.06 vol. percent fibers	119	26.1	13.9
+2.12 vol. percent fibers	19.7	16.9	5.02
+3.18 vol. percent fibers	12.2	7.82	3.88
+4.24 vol. percent fibers	7.96	2.84	3.58

Note: L = latex; M = methylcellulose; SF = silica fume.

Table 7—Fractional increase in volume electrical conductivity due to fibers alone\*

Fiber volume fraction, percent	Fractional increase in conductivity due to fibers alone		
	With L	With M	With M + SF
0.53	1.75	4.81	96.7
1.06	2280	5640	15,000
2.12	13,800	8690	41,600
3.18	22,200	18,800	53,900
4.24	34,000	51,800	58,400

\* Increase is relative to case without fibers but with corresponding dispersant.  
Note: L = latex; M = methylcellulose; SF = silica fume.

the use of electrical conductivity (more exactly, the conductivity ratio explained below) to indicate the degree of fiber dispersion when fibers were present. When fibers were present at a given volume fraction, M + SF yielded the lowest resistivity except at 4.24 vol. percent fibers. The fractional increase in conductivity (reciprocal of resistivity) due to

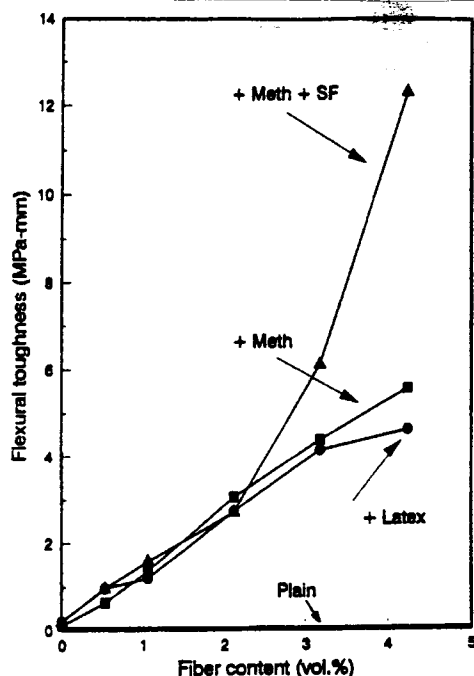


Fig. 5—Dependence of flexural toughness on fiber content

the fibers alone is shown in Table 7. The fractional increase is much higher for M + SF than either M or L for any given fiber volume fraction. The fractional increase is higher for M than L at fiber volume fractions below 1.4 percent but is lower for M than L at fiber volume fractions above 1.5 percent.

Fig. 6 shows the conductivity ratio, i.e., the measured conductivity (at 7 days of curing) as a fraction of the calculated value obtained from the Rule of Mixtures by assuming that the fibers were continuous and parallel along the axis of the conductivity measurement. The matrix conductivity used in the calculation was the measured conductivity for the case without fibers but containing the corresponding additives. The conductivity ratio essentially does not depend on the matrix conductivity. Although the fibers were actually not continuous and not parallel, the assumption of continuous and parallel fibers allows easy calculation and the fraction obtained reflects on a relative scale the effectiveness of the fibers in enhancing electrical conductivity. Since the degree of fiber dispersion is indicated on a relative scale, the model used to calculate electrical conductivity does not matter. This effectiveness depends on the degree of fiber dispersion, the degree of fiber connectivity, and the fiber-matrix contact resistivity. The degree of fiber connectivity greatly increases with increasing fiber volume fraction, thus resulting in the increase of the conductivity ratio with increasing fiber volume fraction (Fig. 6). At a fixed fiber volume fraction, the degree of fiber connectivity increases with increasing degree of fiber dispersion. Thus, at a fixed fiber volume fraction the conductivity ratio reflects the degree of fiber dispersion and the fiber-matrix contact resistivity. A good fiber-matrix interface with no voids is expected to have a lower contact resistivity than a bad interface with voids. Therefore, a high fiber-matrix contact resistivity is expected to be associated

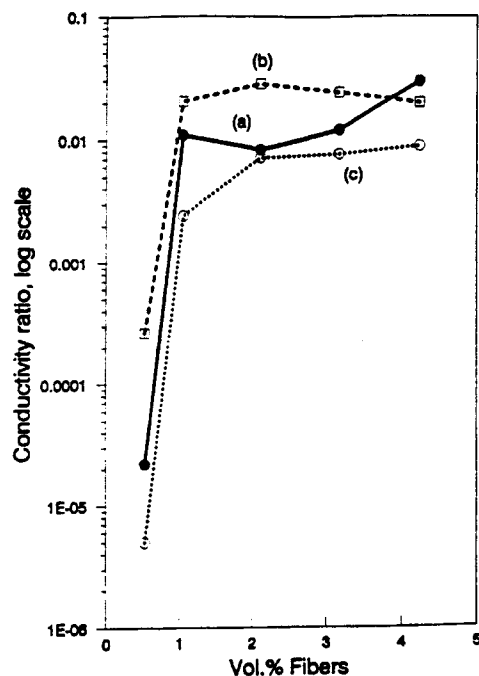


Fig. 6—Variation with carbon fiber volume fraction of ratio of measured volume electrical conductivity to calculated value obtained from Rule of Mixtures by assuming that fibers were continuous and unidirectional along axis of conductivity measurement. Matrix conductivity used in calculation was measured conductivity in case without fibers but containing corresponding additives (a) with methylcellulose; (b) with methylcellulose + silica fume; (c) with latex

with poor mechanical and electrical properties. On the other hand, a low degree of fiber dispersion is also associated with poor mechanical and electrical properties. Therefore, it is not possible to decouple the effect of the degree of fiber dispersion from the effect of the fiber-matrix contact resistivity. However, it has been experimentally shown by the authors in a separate publication<sup>14</sup> that the contact resistivity between steel fiber and cement paste is similar for cement paste with methylcellulose and latex; this has also been shown by the authors in the case of carbon fibers.<sup>15</sup> Therefore, it is reasonable to assume that the effect of the degree of fiber dispersion is more significant than the effect of fiber-matrix contact resistivity in affecting electrical conductivity. Therefore, at a fixed fiber volume fraction the conductivity ratio reflects mainly the degree of fiber dispersion. This ratio is higher for M + SF than for either M or L. M gave a higher fraction than L at all fiber volume fractions. The relative values of this fraction indicate that the degree of fiber dispersion was much higher for M + SF than either M or L. At fiber volume fractions below 1.4 percent, L gave the lowest degree of fiber dispersion. In each dispersant case, the conductivity ratio increased with increasing fiber volume fraction such that the slope of the curve of the conductivity ratio versus fiber volume fraction decreased with increasing fiber volume fraction. The fiber volume fraction at which the slope abruptly changes is the percolation threshold.

As shown in Table 4, the fractional increase in the tensile strength (at 7 days of curing) due to the fibers alone is higher

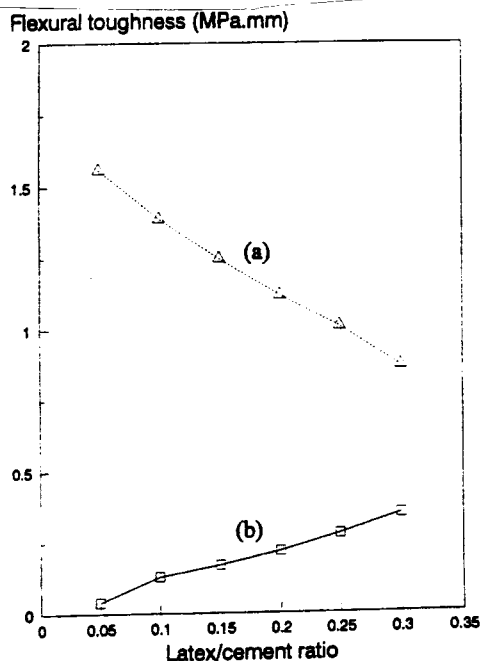


Fig. 7—Effect of latex-cement ratio on flexural toughness when cement paste contained (a) 0.53 vol. percent carbon fibers; (b) no fibers

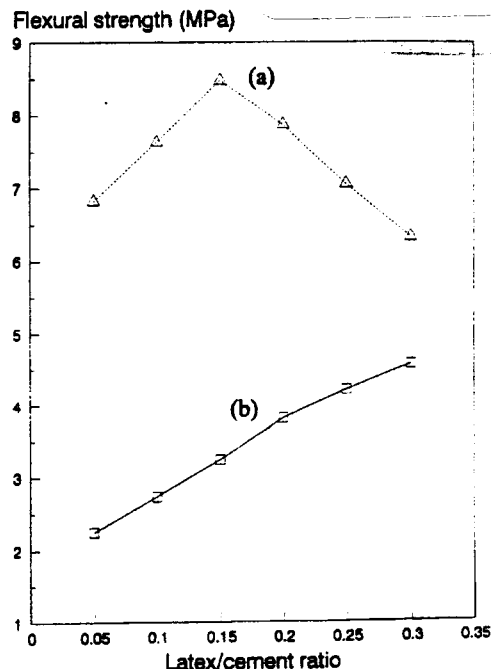


Fig. 8—Effect of latex-cement ratio on flexural strength when cement paste contained (a) 0.53 vol. percent carbon fibers; (b) no fibers

for M + SF than M and higher for M than L for all fiber volume fractions. As shown in Table 5, the fractional increase in the flexural strength due to the fibers alone is higher for M + SF than M and higher for M than L when the fiber volume fraction exceeds 3 percent. These large fractional increases in tensile and flexural strengths in the presence of M + SF are primarily due to the superior degree of fiber dispersion (Fig. 6). At  $\leq 0.7$  vol. percent fibers, the fractional increase in the flexural strength is higher for L than for either M or M + SF (Table 6); this is not due to a superior degree of fiber dispersion but rather is probably due to the superior fiber/matrix bonding and/or lower air void content (Fig. 3) provided by the latex.

Fig. 7 shows the flexural toughness (at 28 days of curing) of cement pastes containing various amounts of latex with 0 and 0.53 vol. percent fibers. The flexural toughness increased monotonically with increasing latex-cement ratio when fibers were absent, but decreased monotonically with increasing latex-cement ratio when fibers were present. At any latex-cement ratio, fiber addition greatly increased the toughness.

Fig. 8 shows the flexural strength (at 28 days of curing) of cement pastes containing various amounts of latex, with 0 and 0.53 vol. percent fibers. Flexural strength increased monotonically with increasing latex-cement ratio when fibers were absent, but first increased and then decreased with increasing latex-cement ratio (so that the flexural strength was maximum at a latex-cement ratio of 0.15) when fibers were present. At any latex-cement ratio, fiber addition increased flexural strength.

Fig. 9 shows the void content (determined by ASTM C 185-91a at 28 days of curing) of cement pastes containing

various amounts of latex with 0 and 0.53 vol. percent fibers. The void content decreased monotonically with increasing latex-cement ratio when fibers were absent, but first decreased and then increased with increasing latex-cement ratio (so that the void content was minimum at a latex-cement ratio of 0.15) when fibers were present. At any latex-cement ratio, fiber addition increased the void content.

The volume electrical resistivity (at 28 days of curing) of cement pastes increased monotonically with increasing latex-cement ratio, whether with 0 or 0.53 vol. percent fibers. At any latex-cement ratio, fiber addition greatly decreased resistivity. Fig. 10 gives the ratio of measured conductivity (reciprocal of the measured resistivity) to calculated conductivity (obtained from the Rule of Mixtures by assuming, for the sake of computational simplicity, that the fibers were unidirectional and continuous along the direction of resistivity measurement). In using the Rule of Mixtures, the matrix conductivity was taken as the conductivity of the cement paste without fibers but with the corresponding latex/cement ratio. Fig. 10 shows that the degree of fiber dispersion decreased with increasing latex-cement ratio.

Fig. 7 and 10 point to the conclusion that the degree of fiber dispersion decreased with increasing latex-cement ratio. In other words, the decrease in the flexural toughness with increasing latex-cement ratio when fibers were present is due to the decrease in the degree of fiber dispersion.

Fig. 8 and 9 point to the conclusion that flexural strength was governed by void content, so that it increased when the void content decreased and decreased when the void content increased. The void content decreased with increasing latex-cement ratio from 0.05 to 0.15 when fibers were present because of the matrix, as indicated by the similar decrease

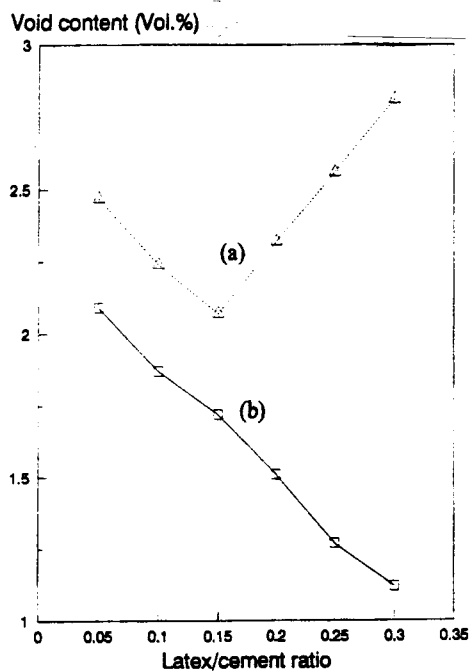


Fig. 9—Effect of latex-cement ratio on void content when cement paste contained (a) 0.53 vol. percent carbon fibers; (b) no fibers

when the fibers were absent (Fig. 9). The void content increased with increasing latex-cement ratio from 0.15 to 0.30 when fibers were present because of the fibers (rather than the matrix, which decreased with increasing latex-cement ratio from 0.15 to 0.30), even though the fiber volume fraction was only 0.53 percent.

For applications requiring high flexural toughness more than high flexural strength, a low latex-cement ratio (as low as 0.05) is recommended. However, a ratio of 0.00 (i.e., no latex at all) is not recommended because of the exceedingly poor fiber dispersion when latex is totally absent (as indicated by visual observation of fiber agglomeration in both the mix and the fracture surface and the large variation in mechanical testing data from sample to sample). If latex is not used at all, silica fume and/or methylcellulose (together with a water-reducing agent) are recommended for helping fiber dispersion.

For applications requiring high flexural strength more than high flexural toughness, a latex-cement ratio of 0.15 is recommended, at least in the case of cement pastes. The optimum latex-cement ratio may change slightly when an aggregate is present.

A low electrical resistivity is desirable for use of carbon fiber reinforced cement as an electrical contact for cathodic protection of steel reinforced concrete.<sup>16</sup> For this application, a low latex-cement ratio (as low as 0.05) is recommended.

When fibers are absent, a high latex-cement ratio (as high as 0.3) is desirable for attaining low void content, high flexural toughness, and high flexural strength. However, when fibers are present, a high latex-cement ratio is undesirable, as it leads to high void content that contributes to low flexural toughness and low flexural strength.

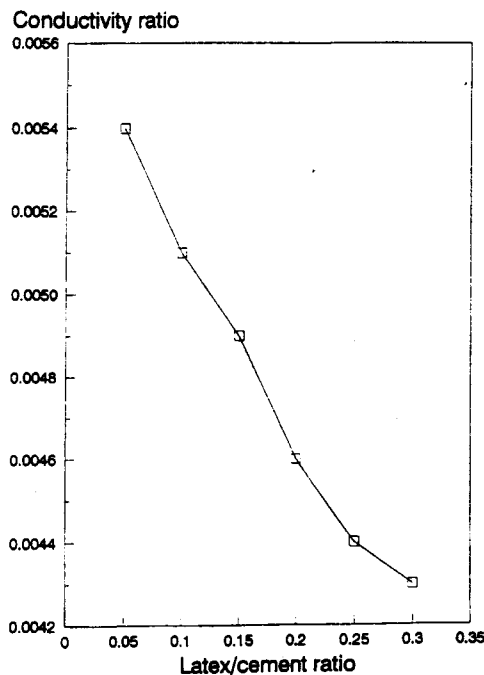


Fig. 10—Effect of latex-cement ratio on measured/calculated conductivity ratio when cement paste contained 0.53 vol. percent carbon fibers

Degree of fiber dispersion and void content are found in this work to govern the flexural properties of fiber reinforced cement so that the flexural properties cannot be predicted from those of the matrix (i.e., the case without fibers).

## CONCLUSIONS

Short carbon fibers in amounts up to 4 vol. percent in cement pastes were effectively dispersed by using any of three dispersants, namely 1) latex (20 percent of the cement weight), 2) methylcellulose (0.4 percent of the cement weight), together with a water-reducing agent, and 3) a combination of methylcellulose (0.4 percent of the cement weight) and silica fume (15 percent of the weight), together with a water-reducing agent. The third dispersant gave the highest flexural strength when the fibers exceeded 2 vol. percent; the first dispersant gave the highest flexural strength when the fibers were below 2 vol. percent and the lowest air void content at all fiber volume fractions; the second dispersant gave the highest air void content at all fiber volume fractions. The third dispersant gave similar or the highest flexural toughness compared to the other two dispersants at fiber volume fractions above 2 percent. Due to the large amount of latex required, the first dispersant was the most expensive. Consideration of both cost and performance led to the choice of the third dispersant as the best.

The degree of fiber dispersion (indicated by the ratio of the measured conductivity to the calculated value obtained from the Rule of Mixtures by assuming that the fibers were continuous and unidirectional along the axis of conductivity measurement) attained by using the third dispersant, together with water-reducing agent in the amount of 3 percent by weight of cement, was higher than those attained by the first



or second dispersant. Thus the fact that the third dispersant resulted in the highest effectiveness of the fibers in enhancing the tensile/flexural properties is due to the highest degree of fiber dispersion. Methylcellulose (second dispersant) was superior to latex (first dispersant) in giving a high degree of fiber dispersion at fiber volume fractions < 1 percent, but latex resulted in superior tensile/flexural properties compared to methylcellulose. This is due to the lower air void content and size and probably superior fiber/matrix bonding provided by the latex.

The following conclusions apply to short carbon fiber (0.53 vol. percent) reinforced cement pastes containing latex at a latex-cement ratio ranging from 0.05 to 0.30. The degree of fiber dispersion decreases monotonically with increasing latex-cement ratio, so the flexural toughness also decreases monotonically with increasing latex-cement ratio in spite of the monotonic increase of the flexural toughness with increasing latex-cement ratio for the cement matrix.

The void content first decreases and then increases with increasing latex-cement ratio, so the flexural strength first increases and then decreases with increasing latex-cement ratio in spite of the monotonic decrease of the void content and the monotonic increase of the flexural strength with increasing latex-cement ratio for the cement matrix. The optimum latex-cement ratio for lowest void content and highest flexural strength is 0.15. The degree of fiber dispersion and the void content govern the flexural properties, so that the flexural properties for the case without fibers do not scale with those for the case with fibers. A high latex-cement ratio is desirable for high flexural strength and toughness when fibers are absent, but is not desirable when fibers are present. For high flexural toughness or low electrical resistivity, the optimum latex-cement ratio is 0.05; for high flexural strength, it is 0.15.

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