# Latex-modified cement mortar reinforced by short carbon fibres

*XIAOMING YANG and D.D.L. CHUNG*

*(State University of New York at Buffalo, USA)*

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The addition to cement mortar of 0.37 volume% (vol%) of short, pitch-based carbon fibres, together with latex (styrene–butadiene) and antifoam, increased the flexural strength by 54% and the compressive strength by 30% at 28 days of curing; relative to mortar containing latex and antifoam, the fibres increased the flexural strength by 33%, had little effect on the compressive strength and increased the price by 17%. In addition, the fibres increased the flexural toughness and decreased the electrical resistivity. Fibre contents $\geqslant$ 1.1 vol% resulted in substantial degradation of the compressive strength and slight degradation of the flexural strength at 7 days of curing, relative to the strengths at a fibre content of 0.37 vol%. The optimum latex/cement ratio was 0.2. The latex served to disperse the fibres and increase the bonding between the fibres and the matrix. Partial replacement of cement by silica fume in mortar containing latex, antifoam and fibres did not increase the flexural strength.

**Key words:** *composite materials; fibre-reinforced cement; latex modifier; flexural strength; compressive strength; composition; curing time; short carbon fibres*

Latex-modified cement mortars and concretes are attractive because the latex addition substantially increases the flexural strength and the compressive strength[1,2]. On the other hand, fibre-reinforced mortars and concretes are attractive because the fibre addition substantially increases the flexural toughness and, in some cases, it increases the flexural strength as well[3–5]. It is therefore appropriate to combine these two methods.

Among fibres, carbon fibres are attractive because of their chemical stability, low density, high strength, high modulus and rapidly decreasing cost. An increase of 100% in the flexural strength was achieved in mortar at 7 days of curing with the addition of short (5 mm long) pitch-based carbon fibres in the amount of only 0.2 volume% (vol%), together with methylcellulose (a dispersant) and an antifoam[5]. Larson *et al.*[6] added short (1.7 mm long) carbon fibres in an amount of 3 vol% to latex-modified mortar and tested the resulting composites at 7 days of curing, but the fractional increase in strength due to the carbon fibre addition was not determined. Soroushian *et al.*[7] added short (1.5 mm long) carbon fibres in the amount of 3 vol% to latex-modified mortar containing silica fume and tested the resulting composites at 14 days of curing, but the fractional increase in strength due to the carbon fibre addition was again not determined. On the other hand, the latex improved the bonding between the fibres and the matrix[6,7], increased the flexural toughness, decreased the compressive strength, had little effect on the flexural strength, increased the freeze-thaw durability and decreased the drying shrinkage, relative to the case without latex. (Both cases with and without latex contained silica fume and carbon fibres[7].)

This work provides a systematic study of the effect of different volume fractions of carbon fibres on the flexural and compressive properties of latex-modified cement mortar at curing ages of up to 28 days. With 0.73 vol% of carbon fibres in latex-modified mortar, a flexural strength of 11.3 ($\pm$5%) MPa was attained in this work at 7 days of curing; this corresponds to a flexural strength increase of 54% relative to the unreinforced latex-modified mortar. Almost the same 7-day flexural strength was reported in Reference 6 for latex-modified mortar containing 3 vol% of carbon fibres. With 0.73 vol% of carbon fibres in latex-modified mortar, a flexural strength of 12.7 ($\pm$1.8%) MPa was attained in this work at 14 days of curing; about the same 14-day flexural strength, namely 13 MPa, was reported in Reference 7 for latex-modified mortar containing 3 vol% of carbon fibres. Furthermore, the systematic study of this work showed

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**Table 1. Properties of carbon fibres**

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

that, among latex-modified mortars containing carbon fibres in amounts from 0.37 to 5.1 vol%, the amount of 0.73 vol% yielded the highest 7-day flexural strength.

The addition of carbon fibres to mortars or concretes is known to decrease the compressive strength due to the air content introduced by the fibre addition[5]. For example, the addition to plain concrete of carbon fibres in the amount of 0.2 vol%, together with methylcellulose and a defoamer, decreased the 7-day compressive strength by 14% [5]. In contrast, this work showed that the addition to latex-modified mortar of carbon fibres in amounts of 0.37 and 0.73 vol% had negligible effect on the compressive strength of the latex-modified mortar. This makes carbon fibre-reinforced latex-modified mortars more attractive than the counterpart without latex.

The technique for dispersing the fibres is critical to the performance of fibre-reinforced concretes. Dispersing carbon fibres in water containing methylcellulose (a dispersant), together with an antifoam, was shown to work well[5]. This work provides another way of dispersing the fibres, namely the use of latex, together with an antifoam.

## *EXPERIMENTAL*

### *Raw materials*

The short carbon fibres were pitch-based and unsized. The nominal fibre length (given by the fibre manufacturer, which is Ashland Petroleum Co) was 5.1 mm. The fibre properties are shown in Table 1. The aggregate used was natural sand, the particle size analysis of which is shown in Fig. 1. Table 2 describes the various raw materials used. The latex was a styrene–butadiene polymer emulsion; unless stated otherwise, it was used in the amount of 20% by weight of cement. The antifoam (an emulsion) used was in the amount of 0.1% by weight of the latex; it was used in all samples except the plain mortar. The water reducing agent used was TAMOL SN, which was used in the amount of 1% by weight of the cement; it was used in all samples, including the plain mortar. Unless stated otherwise, the water/cement ratio was 0.30 and the sand/cement ratio was 1.0.

### *Mixing procedure*

A Hobart mixer with a flat beater was used for mixing. At first, the latex, antifoam and the carbon fibres were mixed for less than about 1 min. Then this mixture and the cement, water, sand and water reducing agent were mixed for 5 min. (The mixing time should be sufficient,

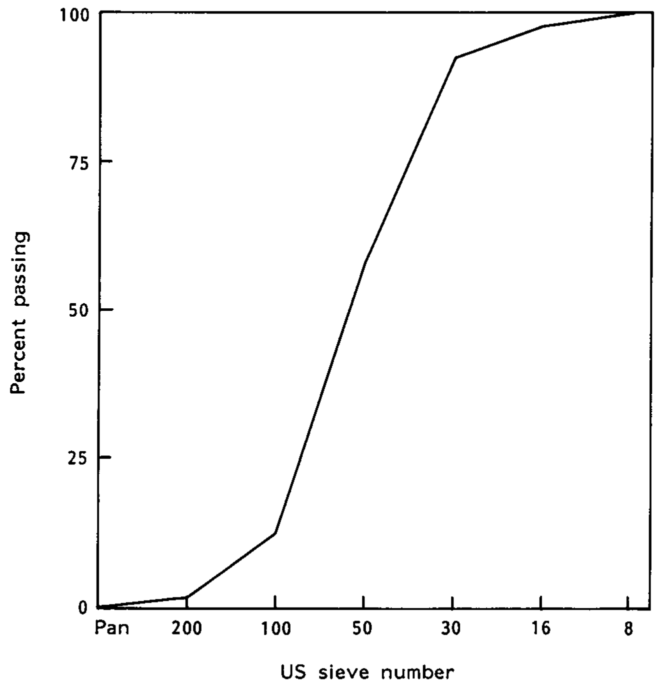

Fig. 1 Particle size distribution of the sand

but as short as possible in the second step of the mixing.) The latex greatly helped the dispersion of the fibres.

### *Curing procedure*

The specimens were demoulded after 1 day and then allowed to cure. Unless stated otherwise, curing was carried out at room temperature in air (not in a moist room).

### *Mechanical testing procedure*

Flexural testing was performed on all samples by three-point bending (ASTM C348-80), with a span of 229 mm (9 in). The sample size was 40 × 40 × 160 mm. For compressive testing, the sample size was 50.8 × 50.8 × 50.8 mm ( 2 × 2 × 2 in) (ASTM C109-80). Nine samples of each composition were used for each type of test. The flexural toughness was calculated from the area under the load/deflection curve obtained in flexural testing.

## *RESULTS*

### *Latex-modified mortar without fibres*

Fig. 2 shows that the antifoam greatly increased the 7-day flexural strength for the case without fibres. Due to the foam produced by the latex upon mixing with cement and water, the antifoam was necessary to change the surface energy of the latex.

Fig. 3 shows that curing in air resulted in much higher flexural strength than curing in water for the case without fibres. Therefore, curing was performed in air in this work, unless stated otherwise.

The effects of the water/cement ratio, the latex/cement ratio and the sand/cement ratio on the 7-day flexural strength are shown in Figs 4, 5 and 6 respectively for the case without fibres. The flexural strength decreased with increasing water/cement ratio (Fig. 4), was

**Table 2. List of raw materials**

| Material | Source |
|---|---|
| Portland cement<br>Type I | Lafarge Corporation (Southfield, MI) |
| Natural sand<br>100% passing 2.36 mm sieve<br>99.91% $SiO_2$ | Pine Hill Ready Mix Concrete and Materials (Buffalo, NY) |
| TAMOL SN<br>Sodium salt of a condensed naphthalenesulphonic acid, 93–96%<br>Water, 4–7%<br>Tan, free-flowing powder | Rohm and Hass Company (Philadelphia, PA) |
| Latex 460NA<br>Styrene–butadiene, 40–60%<br>Water, 40–60%<br>Stabilizer, 1–5% | Dow Chemical Corp (Midland, MI) |
| Antifoam 2410<br>Polydimethylsiloxane, 10%<br>Water, preservatives and emulsifiers, 90% | Dow Corning Corp (Midland, MI) |
| Silica fume A | Elkem Materials Inc (Pittsburgh, PA) |
| Silica fume B | TAM Ceramics (Niagara Falls, NY) |
| Carboflex<br>carbon fibres | Ashland Petroleum Company (Ashland, KY) |

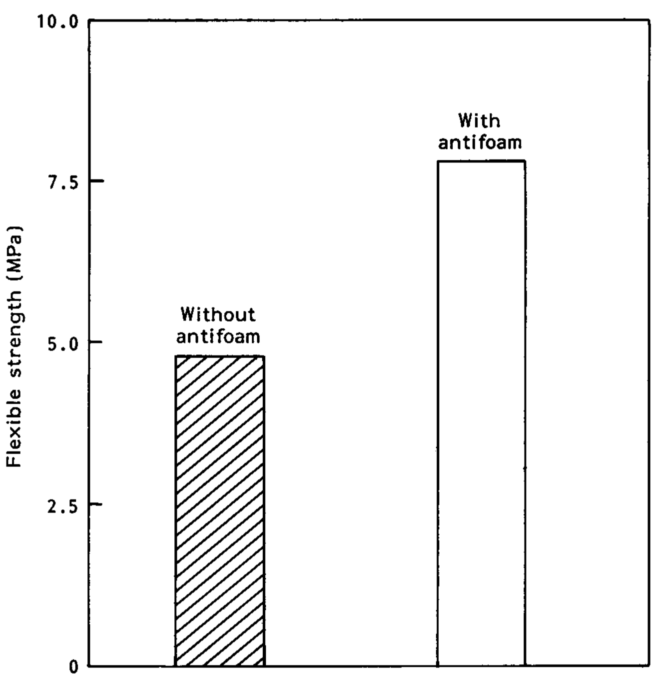


Fig. 2 Effect of antifoam on the flexural strength of latex-modified mortar without fibres

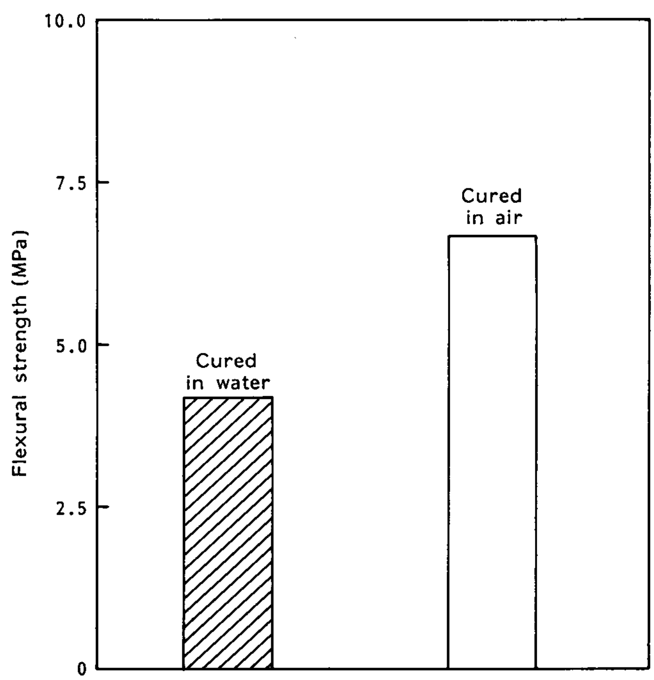


Fig. 3 Effect of curing condition on the flexural strength of latex-modified mortar without fibres

maximum at a latex/cement ratio of 0.2 (Fig. 5), and decreased with increasing sand/cement ratio (Fig. 6). The trends in Figs 4 and 6 are as expected. That the flexural strength decreased sharply as the latex/cement ratio was increased from 0.2 to 0.3 (Fig. 5) is because excessive latex resulted in a polymer-matrix composite. Therefore, in this work, the latex/cement ratio was 0.2 and the sand/cement ratio was 1, unless stated otherwise. The water/cement ratio was kept at the minimum necessary for sufficient fluidity in the mix.

### *Latex-modified mortar with carbon fibres*

Table 3 shows the flexural strength of plain mortar, latex-modified mortar without fibres and latex-modified mortars with various volume fractions of carbon fibres. The water/cement ratio was 0.3 for all types of sample

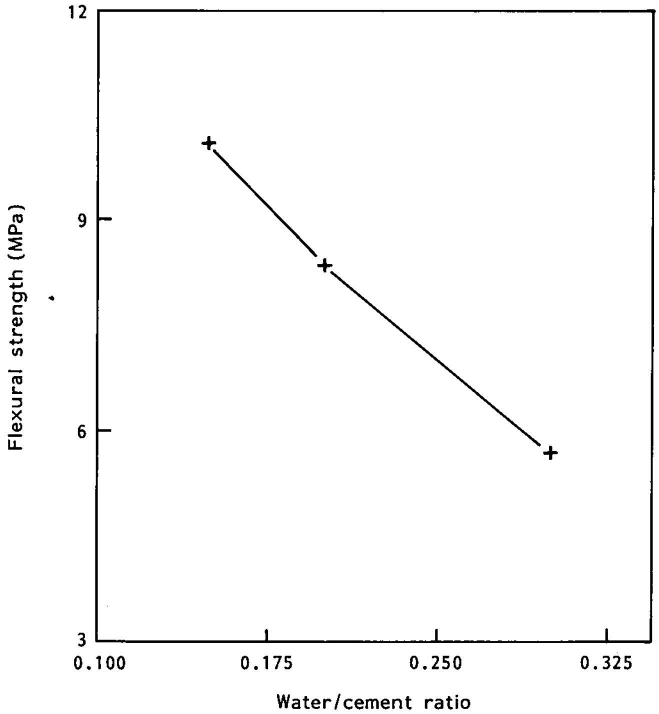

Fig. 4 Effect of the water/cement ratio on the flexural strength of latex-modified mortar without fibres

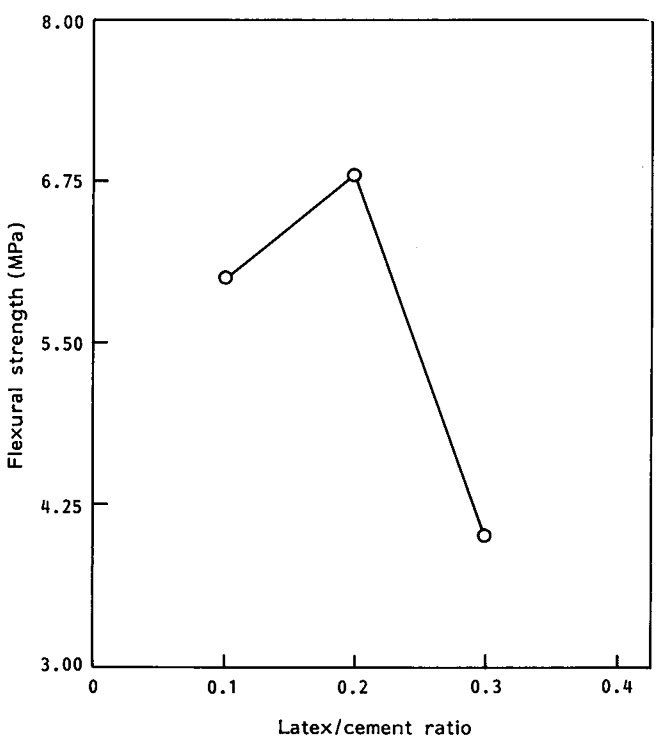

Fig. 5 Effect of the latex/cement ratio on the flexural strength of latex-modified mortar without fibres

except the two types (rows 9 and 10 of Table 3) with the highest filler volume fractions. A high fibre content necessitated a water/cement ratio of 0.5. Due to the fact that the difficulty of fibre dispersion increased with increasing fibre content, the flexural strength was highest at an intermediate fibre content. At 7 days of curing, the highest flexural strength was obtained at a fibre content of 0.73 vol%; at 28 days of curing, it was obtained at a fibre content of 2.2 vol%. Comparision of

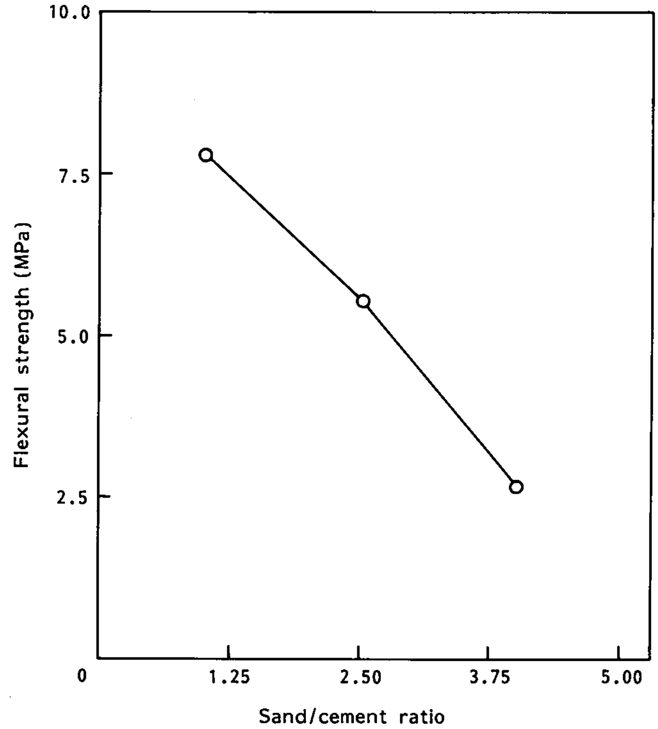

Fig. 6 Effect of the sand/cement ratio on the flexural strength of latex-modified mortar without fibres

rows 1 and 2 of Table 3 shows that the latex was effective for increasing the flexural strength. Comparison of rows 2 and 3 shows that fibres are also effective, even in an amount of just 0.37 vol%. As an increase in the fibre content to 0.73 vol% did not substantially further increase the flexural strength and the fibres are relatively expensive, a fibre content of 0.37 vol% was optimum. For all types of samples, the flexural strength increased with increasing curing age, as expected.

Table 3 also shows the compressive strength. Comparison of rows 1 and 2 shows that the latex substantially increased the compressive strength. Comparison of rows 2, 3 and 4 shows that fibres in amounts of up to 0.73 vol% did not affect the compressive strength. However, increase of the fibre content to $\geq$ 1.1 vol% caused the compressive strength to degrade, though the compressive strength remained higher than or comparable to that of plain mortar.

The compressive and flexural strength results, together with materials costs, indicate that a fibre content of 0.37 vol% was optimum.

Fig. 7 shows the load/deflection curve during flexural testing at 28 days of curing for samples corresponding to rows 1, 2 and 7 of Table 3. The flexural toughness of plain mortar was increased by 43% by the latex alone, while that of latex-modified mortar was increased by 90% by the fibres (2.2 vol%). The increase in flexural toughness was due to the increase in flexural strength as well as the increase in ductility.

Table 4 shows the effect of silica fume on the flexural strength at 7 days of curing. Two types of silica fume, labelled A and B, were used. They are described in Table 5. The use of silica fume B (15% replacement of the cement) in latex-modified mortar substantially

**Table 3. Flexural and compressive strengths at various curing ages**

| | | Fibre/ cement ratio (%) | Fibre volume fraction (%) | Flexural strength (MPa) 7 days | 14 days | 28 days | Compressive strength (MPa) 7 days | 28 days |
|---|---|---|---|---|---|---|---|---|
| 1 | Plain | 0 | 0 | 5.57(±7.5%) | 7.39(±3.7%) | 8.31(±8.7%) | 21.0(±10.4%) | 29.9(±12.1%) |
| 2 | + L | 0 | 0 | 7.36(±8.0%) | – | 9.64(±2.3%) | 32.3(±3.6%) | 40.4(±5.0%) |
| 3 | + L + F | 0.5 | 0.37 | 11.0(±5.8%) | 12.2(±3.0%) | 12.8(±1.3%) | 32.6(±13.0%) | 38.8(±3.7%) |
| 4 | + L + F | 1.0 | 0.73 | 11.3(±5.1%) | 12.7(±1.8%) | 13.4(±3.3%) | 32.7(±14.3%) | 38.2(±10.7%) |
| 5 | + L + F | 1.5 | 1.1 | 9.02(±6.4%) | – | – | 27.2(±8.0%) | – |
| 6 | + L + F | 2.0 | 1.5 | 9.10(±13.4%) | – | 12.7(±10.0%) | 28.3(±4.7%) | 32.0(±5.3%) |
| 7 | + L + F | 3.0 | 2.2 | 8.03(±9.1%) | 12.1(±3.4%) | 15.3(±4.2%) | 26.7(±10.1%) | 30.6(±8.1%) |
| 8 | + L + F | 4.0 | 2.9 | 8.17(±15.6%) | – | 14.2(±3.5%) | 26.0(±8.0%) | 29.1(±9.1%) |
| 9 | + L + F* | 5.0 | 3.7 | 10.05(±3.9%) | – | – | – | – |
| 10 | + L + F* | 7.0 | 5.1 | 9.35(±5.6) | – | – | – | – |

*Water/cement ratio = 0.50
Note: L = latex; F = fibres

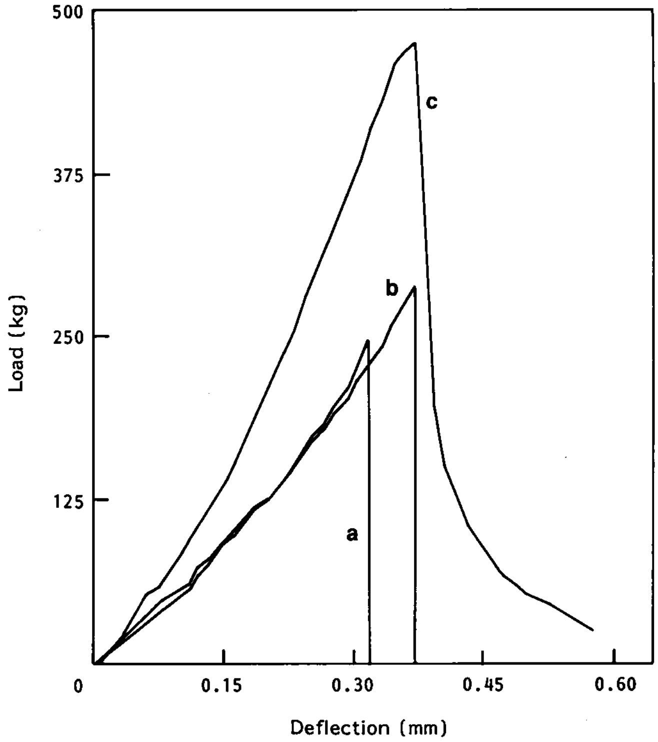


Fig. 7 Load/deflection curve during flexural testing of: (a) plain mortar; (b) mortar with latex; and (c) mortar with latex and 2.2 vol% carbon fibres

increased the flexural strength, but the use of silica fume A (10% replacement of the cement) in latex-modified mortar substantially decreased the flexural strength. The addition of fibres to the latex-modified mortar containing silica fume (A or B) increased the flexural strength, though by a smaller fraction than the counterpart without silica fume (Table 3). Comparison of Table 3 (row 4) and Table 4 (row 4) shows that the use of silica fume B on top of the fibres in latex-modified mortar had negligible effect on the flexural strength.

Table 6 shows that electrical resistivity at 28 days of curing, as measured by the four-probe method, with silver paint as electrical contacts. Three samples of each composition were tested. The resistivity was not affected by the latex addition, but was decreased by the fibre addition. The resistivity decreased with increasing fibre content up to 1.5 vol%, such that the largest drop in resistivity occurred as the fibre content was increased from 0.73 to 1.5 vol%. That the resistivity did not drop much as the fibre content increased beyond 1.5 vol% was due to the relative difficulty in dispersing the fibres when the fibre content was high.

**Table 4. Effect of silica fume on the flexural strength at 7 days of curing**

| | | Flexual strength (MPa) |
|---|---|---|
| 1 | Plain | 5.57(±7.5%) |
| 2 | + latex | 7.36(±8.0%) |
| 3 | + latex + silica fume B | 9.80(±4.7%) |
| 4 | + latex + silica fume B + fibres* | 10.8(±8.0%) |
| 5 | + latex + silica fume A | 5.81(±3.7%) |
| 6 | + latex + silica fume A + fibres* | 6.80(±4.2%) |
| 7 | + latex + fibres* | 11.0(±5.8%) |

*0.5% of the weight of the cement, or 0.37 vol% of mortar

Fig. 8 shows scanning electron microscope (SEM) photographs of the fracture surfaces after flexural testing at 28 days of curing. In plain mortar, the bonding between the sand and cement was quite poor, as shown by the exposed sand in Fig. 8(a). In latex-modified mortar (Fig. 8(b)), polymer in the form of grainy patches and hydrate cement crystals in the form of needles were observed particularly in cracks and the sand/cement interface. In mortar containing 0.73 vol% of carbon fibres (no latex) (Fig. 8(c)), much fibre pull-out was observed, as shown by the pulled-out fibres and the smooth tracks left behind by them, and the pulled-out fibres appeared quite clean on the surface; these observations indicate poor bonding between the fibres and the cement matrix. In latex-modified mortar containing 2.2 vol% of carbon fibres (Fig. 8(d)), the fibres were surrounded by the polymer (in the form of grainy patches, as in Fig. 8(b)), less fibre pull-out was observed and the pulled-out fibres had more particulates adhering on the surface; these observations

**Table 5. 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<br>0.15 μm (ave)<br>Range 0.03–0.5 μm<br>20% 0.04 μm | > 10 μm, 19%<br>> 1 μm, 44%<br>> 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 ($m^2$ $g^{-1}$) | 22 (spherical) | 12.5 (spherical) |
| Mohs hardness | 6.5 | – |
| Colour | Grey | Light grey |
| Chemical composition | C 3%<br>FeO 0.1%<br>$Al_2O_3$ 0.36%<br>CaO 0.27%<br>MgO 0.2%<br>3.6% Ion on ignition<br>$Na_2O$, $K_2O$ < 0.5% | Much less C<br>$ZrO_2$ |

**Table 6. Electrical resistivity at 28 days of curing**

| | | Fibre/cement ratio (wt%) | Fibre volume fraction (%) | Resistivity (Ω cm) |
|---|---|---|---|---|
| 1 | Plain | 0 | 0 | $2.71 \times 10^5 (\pm 13\%)$ |
| 2 | + latex | 0 | 0 | $3.23 \times 10^5 (\pm 8.4\%)$ |
| 3 | + latex + fibres | 1.0 | 0.73 | $4.49 \times 10^4 (\pm 11\%)$ |
| 4 | + latex + fibres | 2.0 | 1.5 | $39.4 (\pm 25\%)$ |
| 5 | + latex + fibres | 3.0 | 2.2 | $127 (\pm 5.2\%)$ |
| 6 | + latex + fibres | 4.0 | 3.9 | $23.9 (\pm 8.9\%)$ |

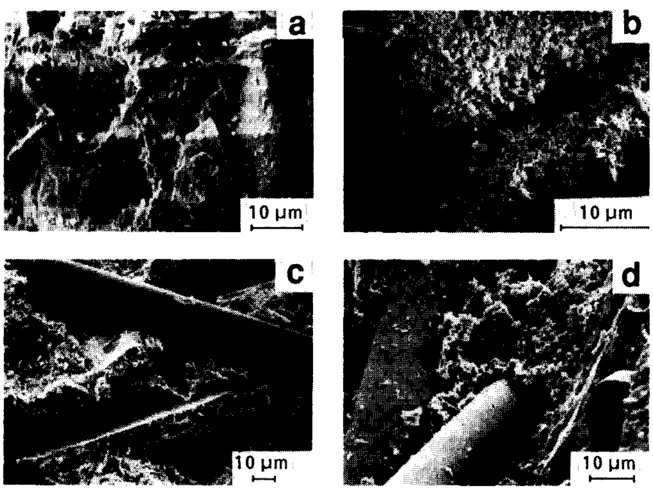


Fig. 8 SEM photographs of the fracture surfaces after flexural testing of: (a) plain mortar; (b) mortar with latex; (c) mortar with 0.73 vol% carbon fibres (no latex); and (d) motar with latex and 2.2 vol% carbon fibres

indicate improved bonding between the fibres and the cement matrix due to the latex addition.

Table 7 shows the materials prices of mortars containing various amounts of carbon fibres. The latex addition was more expensive than the carbon fibre addition up to a fibre content of 1.5% by weight of the cement (or 1.1 vol%). Thus, although the percentage price increase of mortar (row 3 of Table 7) with fibres in the amount of 0.5% by weight of the cement (or 0.37 vol%) is 150% higher than that of plain mortar (row 1 of Table 7), the percentage price increase of this mortar relative to latex-modified mortar (row 2 of Table 7) is just 17%. Therefore, it is economically viable to add carbon fibres to latex-modified mortar for improving the flexural strength and flexural toughness.

## *DISCUSSION*

This work showed by SEM observation that latex is useful in improving the bonding between the carbon fibres and the cement matrix, as previously reported[6,7].

**Table 7. Materials prices of mortars of various formulations**

| | | Fibre/cement ratio (wt%) | Fibre volume fraction (%) | Fractional price increase (%) |
|---|---|---|---|---|
| 1 | Plain | 0 | 0 | 0 |
| 2 | + latex | 0 | 0 | 110 |
| 3 | + latex + fibres | 0.5 | 0.37 | 150 |
| 4 | + latex + fibres | 1.0 | 0.73 | 180 |
| 5 | + latex + fibres | 1.5 | 1.1 | 220 |
| 6 | + latex + fibres | 2.0 | 1.5 | 250 |
| 7 | + latex + fibres | 3.0 | 2.2 | 330 |
| 8 | + latex + fibres | 4.0 | 2.9 | 400 |
| 9 | + latex + fibres | 5.0 | 3.7 | 470 |
| 10 | + latex + fibres | 7.0 | 5.1 | 610 |

Moreover, this work showed that latex helps disperse the carbon fibres, so that no other dispersant needs to be used. If latex is not used, other dispersants are needed, such as methylcellulose[5]. Otherwise, the fibres cling to each other and even to the beater in the mixer. Both latex and methylcellulose require the use of an antifoam.

The weight of latex used per sample in this work was much greater than that of methylcellulose used per sample of the same size in Reference 5. Therefore, the price of carbon fibre-reinforced mortar with latex is much higher than that of carbon fibre-reinforced mortar with methylcellulose. The optimum formulation in Reference 5 contained carbon fibres (in an amount of 0.5% by weight of the cement), methylcellulose, antifoam, triethanolamine, potassium aluminium sulphate, sodium sulphate, TAMOL SN and silica fume A; it corresponds to a materials price increase of 39% relative to plain mortar[5]. The optimum formulation in this work contained carbon fibres (in an amount of 0.5% by weight of the cement), latex, antifoam and TAMOL SN; it corresponds to a materials price increase of 150% relative to plain mortar with TAMOL SN. On the other hand, the compressive strength was decreased by the fibre addition in the case of methylcellulose, but was essentially not affected by the fibre addition in the case of latex.

An increase of 49% in the 7-day flexural strength and an increase of 33% in the 28-day flexural strength were obtained by adding 0.37 vol% of carbon fibres to latex-modified mortar. Relative to plain mortar, the addition of latex and fibres (0.37 vol%) caused the flexural strength to increase by 97%, 65% and 54%, at 7, 14 and 28 days of curing, respectively. In general, the fractional increase in flexural strength at a given fibre content decreased with increasing curing age, at least up to 28 days.

The highest flexural strength (15.3 MPa) was attained by mortar containing latex and fibres (2.2 vol%) at 28 days of curing; it corresponds to a fractional increase in the flexural strength of 84% relative to plain concrete at 28 days. However, at this fibre content, the compressive strength was decreased by 24% relative to the latex-modified mortar without fibres. Therefore, a fibre content of 2.2 vol% is not optimum, especially when cost is also considered. Considering the flexural strength, compressive strength and cost, the optimum formulation contains latex and fibres (0.37 vol%). In contrast, the previous work[6,7] on latex-modified mortar containing carbon fibres used fibres in the amount of 3 vol%. A lower fibre content avoids degradation of the compressive strength, still attains high flexural strength, and decreases the costs of materials and processing.

The fibres increased the flexural toughness by an even larger fraction than the flexural strength. This is because the flexural toughness increase was due to increases in both the flexural strength and the ductility.

The optimum latex/cement ratio is 0.2. The curing of latex-modified mortar in air yielded higher flexural strength than curing in water. This observation is consistent with the suggestion in Reference 7, which also carried out curing in air. The preference for air curing is due to the fact that latex does not need water for curing, in contrast to cement. The use of an antifoam greatly increased the flexural strength of latex-modified mortar, due to the foam introduced by the latex. The importance of an antifoam was also noted in Reference 7.

Silica fume did not increase the flexural strength of mortar containing latex and carbon fibres. The fibres increased the flexural strength of mortar containing latex and silica fume by a much smaller fraction than the case of mortar containing latex but no silica fume. This is probably because both fibres and silica fume adsorbed much water, and their competition for water made the water content below the optimum. Indeed, the mortar mix with silica fume B (15% replacement of the cement) was lower in fluidity than that with silica fume A (10% replacement of the cement). On the other hand, silica fume B increased the flexural strength of mortar containing latex (but no fibres), whereas silica fume A decreased the flexural strength of the same mortar. The origin of this effect is not completely clear.

## *CONCLUSIONS*

The addition of carbon fibres to latex-modified mortar increased the flexural strength and flexural toughness at all fibre volume fractions up to at least 5.1%, but decreased the compressive strength when the fibre content was $\geq 1.1\%$. Since the flexural strength was similar for fibre contents of 0.37 and 0.73 vol%, economic consideration led to the choice of 0.37 vol% as the optimum fibre content. The latex served to disperse the fibres and increase the bonding between the fibres and the matrix. If latex is not used, another dispersant (e.g., methylcellulose) is necessary. The optimum latex/cement ratio is 0.2. Curing of latex-modified mortar is preferably performed in air rather than water. The use of an antifoam is necessary in latex-modified mortar, whether fibres are present or not. The use of silica fume in latex-modified mortar containing carbon fibres did not increase the flexural strength.

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## AUTHORS

The authors are with the Composite Materials Research Laboratory, Furnas Hall, State University of New York at Buffalo, Buffalo, NY 14260, USA. Correspondence should be directed to Professor Chung.