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Carbon fiber reinforced concrete as an electrical contact material for smart structures

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Abstract. Concrete containing 0.2–0.4 vol.% short carbon fibers was found to exhibit volume electrical resistivity of 10^3–10^5 Ω cm and contact resistivity (between the cured concrete and stainless steel) of 10^3–10^6 Ω cm at zero contact pressure. Increasing the contact pressure from 0 up to 0.05 MPa was sufficient to lower the contact resistivity to a minimum value. Increasing the fiber content to > 0.4 vol.% did not decrease the contact resistivity, but decreased the volume resistivity. The values of the volume and contact resistivities depended on the non-fiber additives (i.e., latex, methylcellulose and silica fume) needed for fiber dispersion. Using latex gave a higher volume resistivity (1×10^5 Ω cm) and a lower contact resistivity (5×10^3 Ω cm^2) than methylcellulose and silica fume; the high volume resistivity was due to the large proportion of latex used; the low contact resistivity was due to the lack of adherent on the surface of fibers protruding from the concrete containing latex.

1. Introduction

Smart concrete structures that are capable of non-destructive flaw detection, allow concrete structures to be repaired before it is too late. This capability is critically needed for highways, bridges and nuclear power plants. This paper describes electrically conducting concrete (made conducting by the addition of carbon fibers) for use as an electrical contact material in smart structures with embedded sensors. For this application to be possible, the electrically conducting material must exhibit a low volume electrical resistivity and a low contact electrical resistivity for contacts between the electrically conducting concrete and metals, such as steel or aluminum, which serve as electrical leads emanating from the embedded sensor. In particular, the contact resistivity of concrete–metal contacts needs to be low even with little or no pressure applied perpendicular to the plane of contact. Thus, in this paper, we investigate the volume electrical resistivity and contact electrical resistivity of mortars containing 0–4 vol.% short carbon fibers and found that the use of the carbon fiber reinforced concrete as an electrical contact material is indeed feasible. Further attractions of carbon fiber reinforced concrete for this application are (i) its corrosion resistance compared with metallic electrical contact materials, and (ii) its simultaneous function as a structure material. In practice, the carbon fiber reinforced concrete may be used in parts of a concrete structure—in locations where electrical contacts are necessary.

The addition of carbon fibers to concrete had been previously found to increase the flexural strength, flexural toughness and freeze–thaw durability, and to decrease the drying shrinkage and the electrical resistivity [1, 2]. Effective use of the fibers requires fiber dispersion, which is enhanced by the addition of methylcellulose [1], latex [2] or silica fume [1]. This paper also investigates the effect of these additives on the electrical properties.

2. Experimental details

2.1. Raw materials

The short carbon fibers were isotropic-pitch-based and unsized. The nominal fiber length was 5.1 mm. The fiber properties are shown in table 1. Fibers in the amount of 0.5% by weight of cement were used. The aggregate used was natural sand, the particle analysis of which is shown in figure 1. Table 2 describes the various raw materials used. Table 3 describes the four types of mortar studied. They are (i) plain mortar, (ii) plain mortar with latex, (iii) plain mortar with methylcellulose and (iv) plain mortar with methycellulose and silica fume. The latex, methylcellulose and silica fume were added to disperse the fibers, but in each category such additives were used whether fibers were present or not in order to obtain the effect of the fiber addition alone. In addition, latex and silica fume served to enhance the fiber-matrix bonding.

The water-reducing agent powder used was TAMOL SN (Rohm and Haas) which contained 93–96% sodium

Table 1. Properties of carbon fibers.

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

salt of a condensed naphthalenesulfonic acid. In general, the slump of carbon-fiber-reinforced cement tends to decrease with increasing carbon fiber content. Therefore, we used various amounts of this water-reducing agent in order to maintain the mortar at a reasonable flow value in the range of 150 ± 50 mm.

The latex was a styrene butadiene polymer emulsion; it was used in the amount of 20% of the weight of the cement. The antifoam (Dow Corning 2410, an emulsion) used was in the amount of 0.1% of the weight of the latex; it was used whenever latex was used.

Methylcellulose, in the amount of 0.4% of the cement weight, was used. The defoamer (Colloids 1010) used along with it was in the amount of 0.13 vol.%; it was used whenever methylcellulose was used.

2.2 Mixing procedure

A Hobart mixer with a flat beater was used for mixing.

For the case of mortar containing latex, the latex, antifoam and carbon fibers were mixed by hand for about 1 min at first. Then this mixture, cement, sand, water and the water-reducing agent were mixed in the Hobart mixer for 5 min.

For the case of mortar 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, sand, water and water-reducing agent (and silica fume, if applicable) were mixed in the Hobart mixer for 5 min.

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

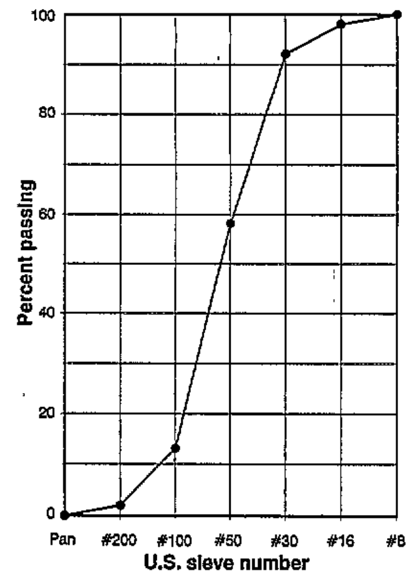

Figure 1. Particle size distribution of the sand.

2.3. Curing procedure

The specimens were 'demolded' after 1 day and then allowed to cure at room temperature in air for 7 days.

2.4 Electrical testing

The volume electrical resistivity was measured by the four-probe method. The specimen size was 130 × 35 × 10 mm. Electrical contacts were made by

Table 2. List of raw materials.

Material	Source
Portland cement Type I	Lafarge Corporation (Southfield, M1)
Natural sand (100% passing 2.36 mm sieve) (99.91% SiO_2)	Pine Hill Ready Mix Concrete and Materials (Buffalo, NY)
TAMOL SN Sodium salt of a condensed naphthalenesulphonic acid (93–96%) water (51–54%)	Rohm and Haas Company (Philadelphia, PA)
Methocel, A15-LV Methylcellulose	Dow Chemical Corporation (Midland, MI)
Colloids 1010 Defoamer	Colloids Inc. (Marietta, GA)
Latex 460NA (Styrene butadiene, 40–60%) (Water, 40–60%) (Stabilizer, 1–5%)	Dow Chemical Corporation (Midland,, MI)
Antifoam 2410 (Polydimethylsiloxane, 10%) (Water, preservatives and emulsifiers, 90%)	Dow Corning Corporation (Midland, MI)
Silica fume	Elkem Materials Inc. (Pittsburgh, PA)
Carboflex Carbon fibers	Ashland Petroleum Company (Ashland, KY)

Table 3. Mix proportions of four types of mortar. Meth = Methylcellulose, SF = silica fume, WR = water reducing agent.

Sample	Fiber vol.%	Water/ cement ratio	Sand/ cement ratio	Latex/ cement ratio	Meth/ cement (%)	SF/ cement ratio	WR/ cement (%)
Plain mortar	—	0.45	1.5	—	—	—	—
Plain mortar with Latex	0	0.3	1	0.2	—	—	—
	0.365			0.2			—
	0.73			0.2			—
	1.5			0.2			2
	2.19			0.2			2
	2.92			0.2			2
	3.65			0.4			—
	4.38			0.6			5
Plain mortar with Meth	0	0.45	1.5	—	0.4	—	—
	0.244						2
	0.488						2
	0.976						2
	1.464						2
	1.952						4
	2.440						6
	2.928						8
Plain mortar with Meth and silica fume	0	0.45	1.5	—	0.4	0.15	2
	0.244						2
	0.488						2
	0.976						4
	1.464						4
	1.952						5
	2.440						8
	2.928						9

silver paint applied along the whole perimeter in four parallel planes perpendicular to the current direction. The inner two contacts were for voltage measurement, while the outer two contacts were for passing a current. Three specimens of each type were tested.

The contact electrical resistivity was measured by sandwiching a $2 \times 2 \times 2\,\text{in}^3$ mortar sample between two stainless steel sheets, applying pressure on the sandwich in the direction perpendicular to the sandwich layers, applying a voltage between the two stainless steel sheets, and measuring the current flowing across the sandwich, which comprised two stainless steel–mortar contacts. Two specimens of each type were tested.

The ability of the mortar to transmit a voltage signal was tested using the configuration of figure 2. A known DC voltage (V_{input} or V_i) was applied between the steel sheets of two steel–mortar–steel sandwiches. The voltage (V_{output}) across the other steel sheets of the two sandwiches was measured. The smaller is the difference ΔV between V_{input} and V_{output}, the better is the ability of the mortar to transmit a voltage signal. This test was conducted as a function of the mortar thickness d and the fiber content in the mortar. Unless stated otherwise, d = 2 cm. Two specimens of each type were tested.

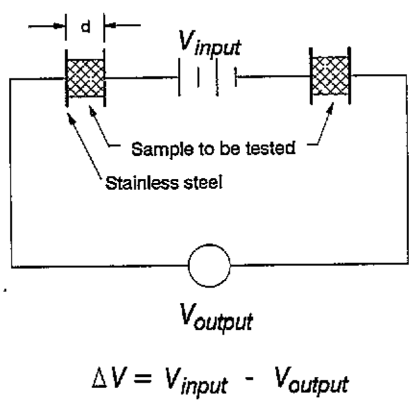

Figure 2. Schematic representation for testing the voltage transmission ability.

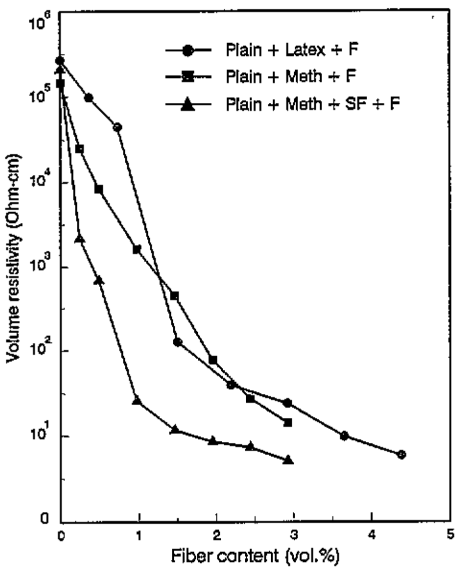

Figure 3. Dependence of the volume resistivity on the fiber content. Meth = methylcellulose, SF = silica fume, F = fibers.

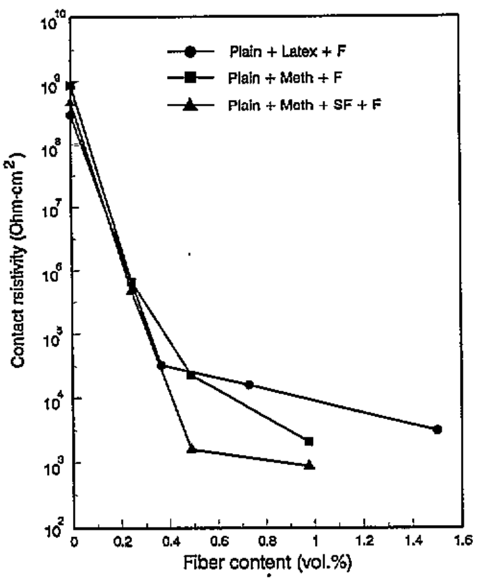

Figure 4. Dependence of the contact resistivity on fiber content. Meth = methylcellulose, SF = silica fume, F = fibers.

3. Results

Figure 3 shows the variation of the volume electrical resistivity with the fiber content for three types of mortar. The three types differ in their additives other than the fibers. For any type, the resistivity dropped by several orders of magnitude (note the logarithmic scale) upon addition of the fibers. The most abrupt decrease occurred at a fiber content below 1.5 vol.%. The lowest volume resistivity at any given fiber content was attained by the mortars containing methylcellulose, silica fume and fibers. In particular, a volume resistivity of 10 Ω cm was attained with 1.5 vol.% fibers.

Figure 4 shows the variation of the contact resistivity with the fiber content when zero compressive stress was applied perpendicular to the plane of the contact. The contact resistivity dropped sharply upon fiber addition up to 0.5 vol.%. The lowest contact resistivity at a fiber content of 0.5 vol.% or above was attained by the mortars containing methylcellulose, silica fume and fibers. In particular, a contact resistivity of 10^3 Ω cm^2 was attained with 0.5 vol.% fibers.

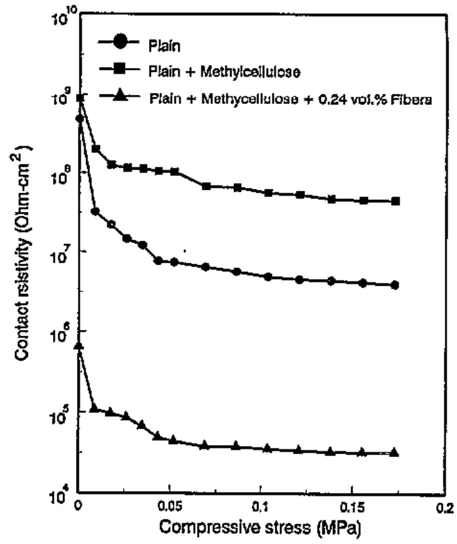

Figure 6. Contact resistivity as a function of compressive stress for mortar containing methylcellulose.

The contact resistivity given in figure 4 is for zero compressive stress applied perpendicular to the plane of the contact. Figures 5–7 show the effect of the stress on the contact resistivity for mortars containing latex, methylcellulose, and methylcellulose and silica fume respectively. In each of the three cases, the addition of latex/methylcellulose/(methylcellulose + silica fume) to plain mortar caused the contact resistivity to increase slightly, while the further addition of carbon fibers caused the contact resistivity to decrease greatly—to levels much lower than that of plain mortar. The minimum compressive stress needed for the contact resistivity to level off to a minimum was about 0.02 MPa for mortar containing latex and 0.37 vol.% fibers (figure 5), 0.05 MPa for mortar containing methylcellulose and

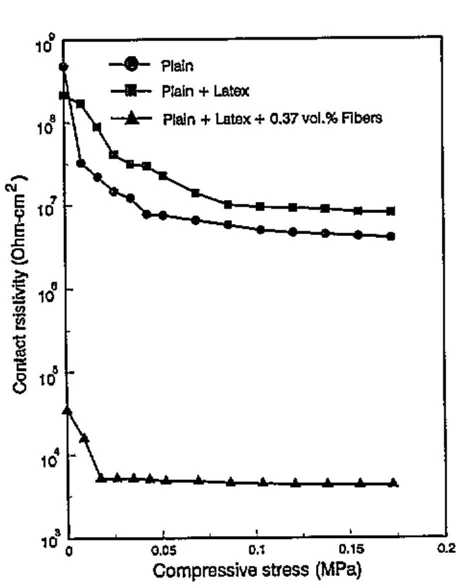

Figure 5. Contact resistivity as a function of compressive stress for mortar containing latex.

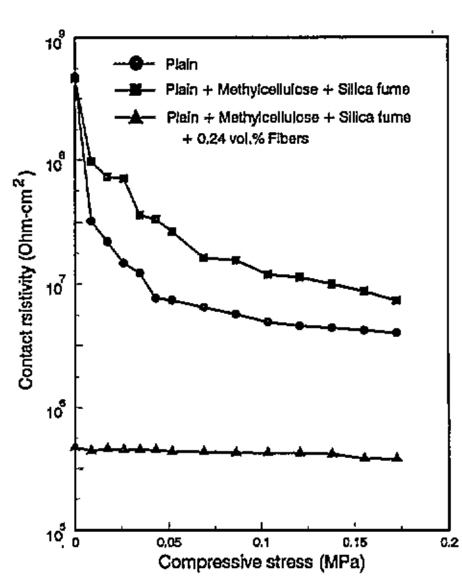

Figure 7. Contact resistivity as a function of compressive stress for mortar containing methylcellulose and silica fume.

0.24 vol.% fibers (figure 6) and 0.00 MPa for mortar containing methylcellulose, silica fume and 0.24 vol.% fibers (figure 7). The leveled-off minimum contact resistivity was 5×10^3, 4×10^4 and $5 \times 10^5\ \Omega\,cm^2$ for mortar containing latex and 0.37 vol.% fibers (figure 5), mortar containing methylcellulose and 0.24 vol.% fibers (figure 6) and mortar containing methylcellulose, silica fume and 0.24 vol.% fibers (figure 7) respectively.

The leveled-off minimum contact resistivity depended on the cleanliness of the fibers partially protruding from the surface of the mortar. The cleaner the fibers, the lower the contact resistivity, as the adherents were less conductive than the carbon fibers. This explanation is confirmed by the scanning electron microscope (SEM) photographs of the flexural fracture surfaces, as shown in figure 8. Indeed, the mortar containing latex and 0.37 vol.% fibers had clean protruding fibers (figure 8(*a*)) and the lowest value of the leveled-off minimum contact resistivity. The mortar containing methylcellulose and 0.24 vol.% fibers had particulate adherents (cement particles) partly covering the protruding fibers (figure 8(*b*)) and the intermediate value of the leveled-off minimum contact resistivity. The mortar containing methylcellulose, silica fume and 0.24 vol.% fibers had most adherents covering the protruding fibers (figure 8(*c*)) and the highest value of the leveled-off minimum contact resistivity.

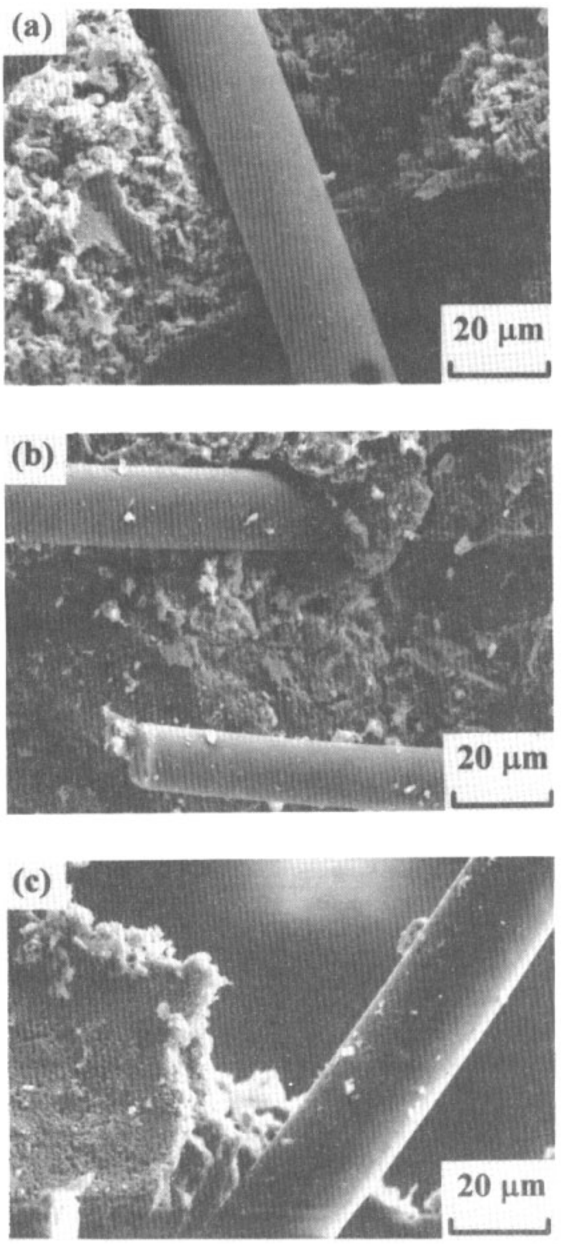

Figure 8. SEM photographs of the flexural fracture surfaces of (a) mortar containing latex and 0.37 vol.% fibers, (b) mortar containing methylcellulose and 0.24 vol.% fibers, and (c) mortar containing methylcellulose, silica fume and 0.24 vol.% fibers.

In contrast, the volume electrical resistivity was lowest for the mortar containing latex and fibers (figure 3). This is because the cleanliness of the partly pulled out fibers is relevant to the contact resistivity, but irrelevant to the volume resistivity.

Both the contact resistivity and the volume resistivity are important for use of the mortar as an electrical contact material. The relative importance of the two properties depends on the length of the contact material in the current direction (the longer it is, the more important is the volume resistivity) and on the area of the contact itself (the greater the area, the less important is the contact resistivity). For the geometry of the samples used in this work, the two properties are comparably important. For the case of the $2 \times 2 \times 2\,in^3$ mortar containing latex and 0.37 vol.% fibers, the minimum contact resistivity of $5 \times 10^3\ \Omega\,cm^2$ corresponded to a contact resistance of

$$\frac{5 \times 10^3\ \Omega\,\mathrm{cm}^2}{(2\,\mathrm{in})^2} = 1.94 \times 10^2\ \Omega$$

while the volume resistivity of $1 \times 10^5\ \Omega\,cm$ corresponded to a volume resistance of

$$(1 \times 10^5\ \mathrm{cm})\frac{(2\,\mathrm{in})}{(2\,\mathrm{in})^2} = 1.97 \times 10^4\ \Omega.$$

For the case of the mortar containing methylcellulose, silica fume and 0.24 vol.% fibers, the minimum contact resistivity of $5 \times 10^5\ \Omega\,cm^2$ corresponded to a contact resistance of

$$\frac{5 \times 10^5\ \Omega\,\mathrm{cm}^2}{(2\,\mathrm{in})^2} = 1.94 \times 10^4\ \Omega$$

while the volume resistivity of $2 \times 10^3\ \Omega\,cm$ corresponded to a volume resistance of

$$(2 \times 10^3\ \Omega\,\mathrm{cm})\frac{(2\,\mathrm{in})}{(2\,\mathrm{in})^2} = 3.94 \times 10^2\ \Omega.$$

Hence, the volume resistance was more important than the contact resistance in the case of the mortar containing latex and 0.37 vol.% fibers, whereas the contact resistance was more important than the volume resistance for the case of the mortar containing methylcellulose, silica fume and 0.24 vol.% fibers.

Figure 9 shows the variation of $\Delta V(V_{input} - V_{output})$ with $V_i\,(V_{input})$ for the experiment of figure 2 for the case of mortars containing latex. All three fiber-containing mortars (with three levels of fiber loading, ranging

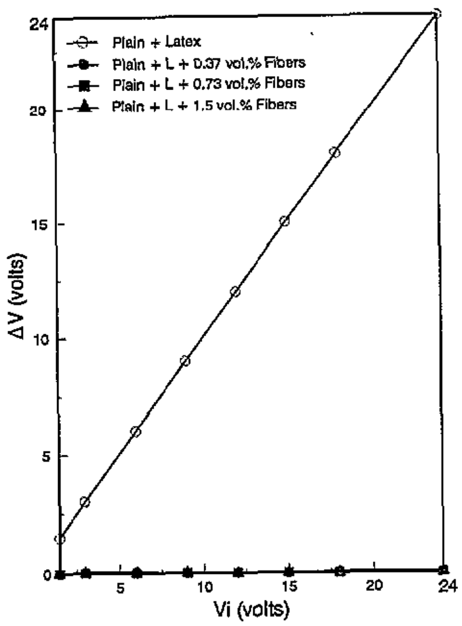

Figure 9. Effect of carbon fibers on the ability of latex-modified mortar to transmit a voltage signal. L = latex; V_i = input voltage; $\Delta V = V_{input} - V_{output}$.

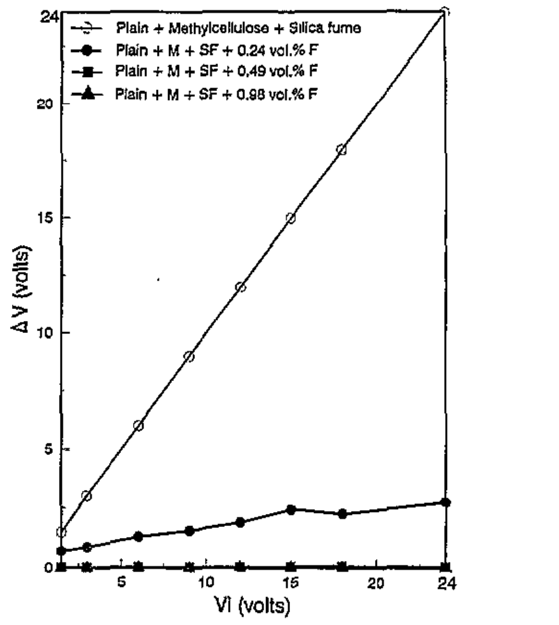

Figure 11. Effect of carbon fibers (F) on the ability to transmit a voltage signal for mortar containing methylcellulose (M) and silica fume (SF).

from 0.37 to 1.5 vol.% fibers) exhibited ΔV of zero, indicating perfect ability to transmit a voltage signal. In contrast, the corresponding mortar without fibers showed ΔV increasing linearly with V_i, such that $\Delta V = V_i$ at $V_i = 24$ V. This means that the mortar without fibers had no ability to transmit a voltage signal.

Similar results for mortars containing methylcellulose and mortars containing both methylcellulose and silica fume are shown in figures 10 and 11 respectively. In both of these cases, perfect ability to transmit a voltage signal was attained when the fiber content was 0.49 vol.% or more; at a fiber content of 0.24 vol.%, the ability was less but still acceptably good.

Figure 12 shows the variation of ΔV with the fiber content when V_i was fixed at 12 V. ΔV decreased abruptly with increasing fiber content up to 0.4 vol.%, at which ΔV became essentially zero. The variation was essentially the same for all three types of mortar. Thus a fiber content of 0.4 vol.% was sufficient for perfect transmission of a voltage signal.

Figure 13 shows a comparison of the voltage transmission ability at $d = 2$ cm and $d = 12$ cm, where d is the length of a mortar sample along the current direction (figure 2). An increase of d from 2 to 12 cm had little or no effect on ΔV. That ΔV was slightly lower at $d = 12$ cm than at $d = 2$ cm for the mortar containing methylcellulose, silica fume and fibers, is attributed to the probably more uniform distribution of carbon

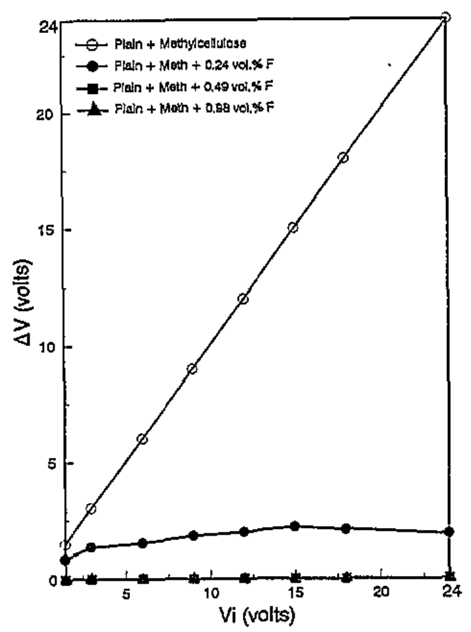

Figure 10. Effect of carbon fibers (F) on the ability to transmit a voltage signal for mortar containing methylcellulose (M).

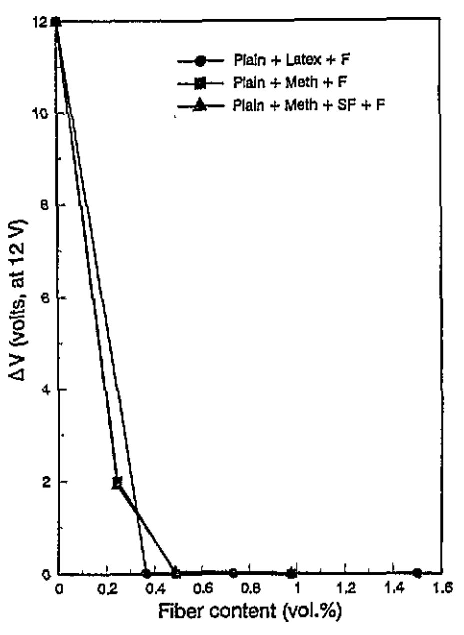

Figure 12. Dependence of ΔV on fiber content. Meth = methylcellulose, SF = silica fume, F = fibers.

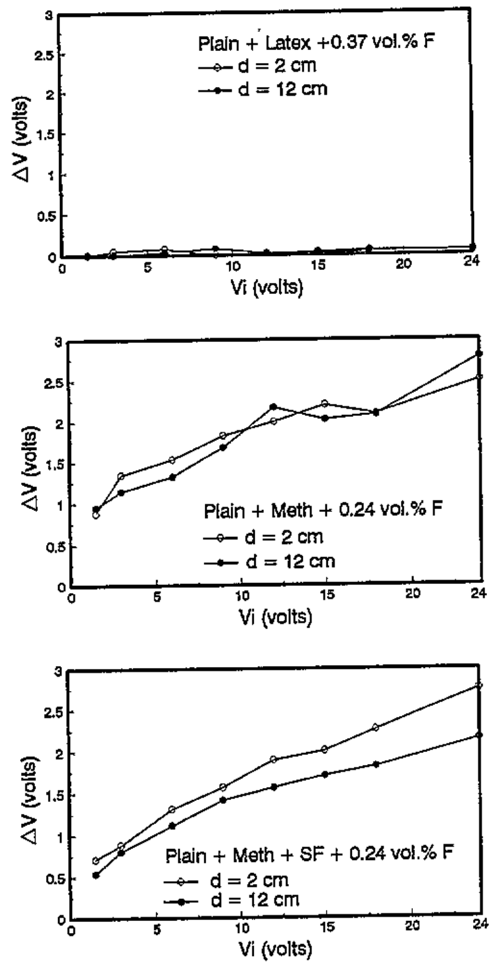

Figure 13. Dependence of ΔV on V_i at $d = 2$ and $d = 12$ cm.

fibers in the larger mortar sample (i.e., the one with $d = 12$ cm).

4. Discussion

This paper used a planar contact between steel and mortar (figure 2) in order to obtain a quantitative measurement of the contact resistivity. However, in practice the contact does not need to be planar. For example, the metal can be a wire embedded in the mortar. The contact resistance consideration still applies to such non-planar contacts. We have actually tested the voltage transmission ability in the case of an aluminum wire that had been partly embedded in a mortar prior to the curing of the mortar. The result was largely similar to that reported here for the planar contacts of steel with mortar (figure 2). It is important to note that a good electrical contact (i.e., one with a low contact resistivity) can be obtained simply by contacting the metal and the cured concrete. It is not necessary to make the contact before the curing of the concrete. This means that electrical probing of the concrete with a metal probe can be conveniently performed in the field at any time after the concrete contact material has cured. Furthermore, a negligible compressive stress (0–0.05 MPa) is needed to be applied at the probe in order to attain a low contact resistivity.

The low volume resistivity of the concrete contact material means that the thickness of the contact material in the current direction can be quite large. In this work, we have tested up to a thickness of 12 cm, but the upper limit of the thickness is expected to be much greater than 12 cm. The value of the upper limit depends on the required accuracy of the voltage transmission.

In this work, the electrical contact between steel and mortar was a pressure contact, though the pressure required was small. An alternative method of making the electrical contact involves the application of silver conducting paint at the contact interface. We did that and found that the silver paint did not improve the quality of the contact compared with the pressure contact. As the silver-paint contact is far more expensive than the pressure contact, the latter is preferred.

In order to avoid crosstalk between different signal lines (emanating from different sensors), different signal lines should end at different contact pads. Thus, a smart structure with multiple sensors will incorporate multiple contact pads in the form of electrically conducting concrete or mortar. For a structure with closely spaced sensors, contact pads in the form of a mortar may be preferred to those in the form of a concrete, as a mortar can be smaller in size, thus allowing small contact pads to be formed.

The drying shrinkage of carbon fiber reinforced concrete is about 90% less than that of plain concrete [1]. Therefore, the pouring of carbon fiber reinforced concrete on to cured (or partially cured) plain concrete results in a much better concrete–concrete bond than pouring plain concrete on to cured (or partially cured) plain concrete [3]. This characteristic adds to the attraction of using carbon fiber reinforced concrete as an electrical contact material in a concrete structure.

In addition to serving as an electrical contact material for a smart concrete structure, carbon fiber reinforced concrete can be used as an electrically conducting overlayer on steel bar reinforced concrete for the application of a voltage for the cathodic protection (corrosion protection) of the steel. The low contact resistivity between a metal contact (for applying the voltage) and carbon fiber reinforced concrete, as shown in this work, is attractive for this application.

5. Conclusion

Mortar rendered electrically conducting by the addition of short carbon fibers can be used as an electrical contact material for metal wires emanating from embedded sensors and for electrical probing from the exterior of the concrete structure. For mortar containing 0.37 vol.% fibers and latex in the amount of 0.2 of the cement weight, the volume resistivity was $1 \times 10^5\ \Omega$ cm and the contact resistivity (between the cured mortar and stainless steel) was $5 \times 10^3\ \Omega\,\mathrm{cm}^2$; the latter was obtained at a contact pressure $\geqslant 0.02$ MPa. For mortar containing 0.24 vol.% fibers, methylcellulose in the amount of 0.4% of the cement weight and silica fume in the amount of 0.15 of the cement weight, the volume resistivity was $2 \times 10^3\,\Omega$ cm and the contact resistivity was $5 \times 10^5\,\Omega\,cm^2$; the latter did not require any contact pressure. The higher volume resistivity of the mortar with latex compared with that with methylcellulose and silica fume is attributed to the high content of latex in the former. The lower contact resistivity of the former is attributed to the lack of adherent on the surface of the fibers protruding from the surface of the former and the large amount of adherent on the surface of the fibers protruding from the latter. A fiber content of 0.4 vol.% was sufficient to attain a minimum contact resistivity, whereas one > 1.5 vol.% was needed to attain a minimum resistivity.

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