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CARBON FIBER REINFORCED MORTAR AS AN ELECTRICAL CONTACT MATERIAL FOR CATHODIC PROTECTION

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ABSTRACT

For a joint between old plain mortar and new mortar (which serves as an electrical contact material for cathodic protection of steel-reinforced old mortar), short carbon fiber addition to the new mortar was found to decrease both the contact resistivity and the new mortar's volume resistivity. Whether the new mortar contained fibers or not, the contact resistance was higher than the new mortar's volume resistance perpendicular to the contact and was lower than the new mortar's volume resistance parallel to the contact. In the presence of latex, the volume resistivity was 3.1×10^5, 1.4×10^3 and 1.2×10^2 Ω.cm and the contact resistivity was 5.9×10^6, 2.7×10^5 and 2.6×10^4 Ω.cm^2 at fiber contents of 0, 0.53 and 1.1 vol.% respectively. Latex addition alone to the new mortar increased slightly both contact resistivity and new mortar's volume resistivity. All resistivities increased very slightly with curing age.

Introduction

A corrosion control method for steel reinforced concrete involves cathodic protection. In this method, electrons are directed to enter the concrete, thus forcing the steel rebars to become the cathode, which does not get corroded. The application of the electrical current requires an electrical contact in the forming of an electrically conductive coating on the concrete. Requirements of the electrical contact material include (i) low volume resistance within the contact material, (ii) low contact resistance and good bonding between the contact material and the underlying concrete, (iii) wear resistance, (iv) oxidation resistance (as most oxides are poor conductors), (v) thermal expansion similar to that of the underlying concrete (for durability under thermal cycling), and (vi) low material and processing costs.

Metals such as zinc, which is deposited on the concrete by thermal spraying, have very low volume resistivity, but they suffer from poor wear resistance, the tendency to oxidise, high thermal expansion coefficient compared to concrete, and high material and processing costs. Moreover, the thermal expansion mismatch and the high temperature involved in thermal spraying mean that interfacial thermal stress is present after cooling to room temperature. This stress will degrade the bonding and increase the contact resistivity between the coating and the underlying concrete.

Besides metals, conductor filled polymers such as coke filled epoxy are used as electrical contact materials on concrete. Conductor filled polymers can be applied as a coating without heating. However, they suffer from poor wear resistance, high thermal expansion coefficient, and high material cost. Their volume resistivity is higher than that of metals. Furthermore, since most polymers are essentially electrically insulating, the use of a polymer as a binder for the conducting filler is expected to result in a high contact resistivity between the coating and the underlying concrete.

Conductor filled mortar is particularly attractive as an electrical contact material on concrete because it can satisfy all of the six requirements listed above. Its volume resistivity is higher than that of metals, but is low enough for cathodic protection application. Unlike metals and filled polymers, conductor filled mortar is wear resistant, comparable in thermal expansion coefficient to the underlying concrete, and low in material and processing costs. An apparent drawback is the poor bonding between the mortar and the underlying old concrete due to the fact that the mortar undergoes drying shrinkage while the underlying old concrete has long finished shrinking. However, this drawback has been alleviated by the addition of short carbon fibers to the mortar [1]. The fiber addition causes the drying shrinkage to decrease [2,3], thereby enhancing the bonding [1]. Moreover, the fiber addition decreases the volume resistivity [2-5] and increases the flexural strength and toughness [2].

Although the contact resistivity (geometry independent) between the electrical contact material and concrete is central to the quality of a contact material for cathodic protection, it has not been reported for any of the electrical contact materials mentioned above. Design of the electrical contact thickness/geometry and choice of the voltage depend on both the volume resistivity of the contact material and the contact resistivity. The contact resistivity has been reported only for the interface between steel and mortar and that between steel and carbon fiber filled mortar [6]; these interfaces are not relevant to electrical contacts to concrete for cathodic protection.

In this paper, carbon fiber filled mortar was evaluated for use as an electrical contact material to concrete for cathodic protection by measuring the contact resistivity between new carbon-fiber-filled mortar and old plain mortar, such that the curing age difference between the new and old mortars was 28 days. In addition, the volume resistivity of the carbon fiber filled mortar was measured. These measurements were made at different carbon fiber contents for the purpose of consideration of the trade-off between cost and performance, as the volume and contact resistivities decrease with increasing fiber content whereas the cost increases with increasing fiber content. Thus, the design parameters of the carbon fiber filled mortar electrical contact material include not only the contact thickness and geometry, but also the fiber content (which affects the contact and volume resistivities). The objective of this paper is to provide the information that is needed for such design.

Experimental Methods

The carbon fibers were short (nominally 5 mm long), unsized and made from isotropic pitch. Their properties are shown in Table 1. They were provided under the trade name Carboflex by Ashland Petroleum Co., Ashland, Kentucky. The dispersion of the fibers requires the use of additives, such as latex, methylcellulose and/or silica fume [4]. Latex is used in this work in the amount of 20% by weight of cement. The latex (Dow Chemical Corp., Midland, MI, 460NA) was a styrene butadiene copolymer emulsion. Used along with latex was an antifoam agent (Dow Corning, Midland, MI, 2410, an emulsion) in the amount of 0.5% by weight of latex. In addition, a water reducing agent (WR) was used

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	3.0×10^{-3} Ω cm
Specific gravity	1.6 g cm $^{-3}$
Carbon content	98 wt.%

in the amount of 1.5% by weight of cement. The WR was TAMOL SN (Rohm and Haas, Philadelphia, PA) which contained 93-96% sodium salt of a condensed naphthalene sulfonic acid. The water/cement ratio was 0.23. The slump was 160-170 mm, as determined conventionally. The fiber content was 0, 0.5% or 1.0% by weight of cement (i.e., 0, 0.53 or 1.1 vol.% of mortar). The sand was natural sand (100% passing 2.36 mm sieve, 99.9% SiO_2) from Pine Hill Ready Mix Concrete and Materials, Buffalo, NY. The particle size analysis of the sand is shown in Fig. 1 of Ref. 6. The sand/cement ratio was 1.0. The cement was Portland cement, Type I, from Lafarge Corporation (Southfield, MI).

The latex, antifoam agent and fibers first were mixed by hand for ~ 1 min. Then this mixture, sand, cement, water and WR were mixed in a Hobart mixer with a flat beater for 5 min. After pouring the mix into oiled molds, a vibrator was used to facilitate compaction and decrease the amount of air bubbles. The specimens were demolded after 1 day (except for the old mortar of a joint between old and new mortars) and then allowed to cure at room temperature (25°C) and room humidity (~ 33% relative humidity) in air.

The volume electrical resistivity was measured by the four-probe method, using silver paint for the electrical contact. The DC current used ranged from 0.1 to 4 A. The contact electrical resistivity measurements were conducted on mortar-mortar joints of the configuration shown in Fig. 1. The new mortar was cast 28 days after the old mortar was cast. An electrical current was passed in the direction perpendicular to the joint. Electrical contacts were made by silver paint applied along the whole perimeter in four parallel planes (two in each half of the specimen, symmetrically) perpendicular to the current direction. The inner two contacts were used for voltage measurements, while the outer two contacts were used for passing a current. The four-probe geometry allowed elimination of the silver-mortar contact potential drop at the voltage probes. The volume electrical resistances of the two halves

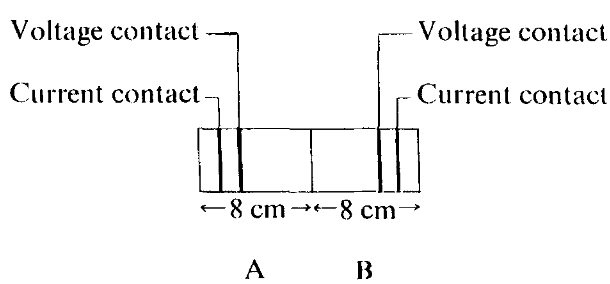

Fig. 1 Configurations for measuring the contact resistivity between old mortar (A) and new mortar (B).

within the voltage probes, as calculated from the separately determined volume resistivity of each half at the corresponding curing age, were subtracted from the measured resistance in order to obtain the new-to-old mortar contact resistance. The contact resistance, multiplied by the contact area, gave the contact resistivity. Six specimens of each type were tested.

Results and Discussion

Tables 2 and 3 give the volume resistivity and contact resistivity respectively. Both resistivities increased very slightly with increasing curing age. Latex addition increased both resistivities slightly, but fiber addition decreased them greatly.

Consider, for example, a joint of area 100 x 100 cm between old and new mortars, such that the new mortar is 1 cm thick. This configuration resembles that encountered when the new mortar serves as an electrical contact material for cathodic protection of steel-reinforced old mortar or concrete. The values shown in Table 2 for the volume resistivity and in Table 3 for the contact resistivity allow calculation of the volume resistance of the new mortar perpendicular and parallel to the joint, as well as the contact resistance of the joint. The volume resistance (R_v) of the new mortar was calculated by using the equation

$$R_v = \rho_v \frac{\ell}{A} \quad , \tag{1}$$

where ρ_v is the volume resistivity. In the direction perpendicular to the joint, ℓ = 1 cm and A = (100 x 100) cm^2; in the direction parallel to the joint, ℓ = 100 cm and A = (100 x 1) cm^2. The contact resistance (R_c) perpendicular to the joint was calculated by using the equation

$$R_c = \frac{\rho_c}{A} \quad , \tag{2}$$

where ρ_c is the contact resistivity and A = (100 x 100) cm^2. Table 4 gives the results of these calculations. Whether the new mortar contained fibers or not, the contact resistance was higher than the new mortar's volume resistance perpendicular to the joint and was less than the new mortar's volume resistance parallel to the joint. Hence, resistances perpendicular to the joint was dominated by

Table 2. The volume resistivity (Ω.cm) at different curing ages (days).
A:plain; B:+L; C:+L+0.53 vol.% fibers; D:+L+1.1 vol.% fibers.

	1 d	3 d	7 d	10 d	14 d	20 d	24 d	28 d	56 d
A	1.12×10^5 (±9%)	1.29×10^5 (±10%)	1.41×10^5 (±6%)	1.54×10^5 (±5%)	1.65×10^5 (±4%)	1.71×10^5 (±5%)	1.81×10^5 (±6%)	1.83×10^5 (±7%)	1.85×10^5 (±5%)
B	2.65×10^5 (±7%)	2.72×10^5 (±8%)	2.77×10^5 (±9%)	2.91×10^5 (±6%)	3.02×10^5 (±5%)	3.07×10^5 (±6%)	3.12×10^5 (±5%)	3.14×10^5 (±5%)	3.15×10^5 (±4%)
C	1.20×10^3 (±3%)	1.22×10^3 (±2%)	1.23×10^3 (±2%)	1.29×10^3 (±3%)	1.33×10^3 (±5%)	1.37×10^3 (±2%)	1.39×10^3 (±1%)	1.41×10^3 (±1%)	1.42×10^3 (±1%)
D	1.12×10^2 (±2%)	1.13×10^2 (±3%)	1.13×10^2 (±2%)	1.14×10^2 (±1%)	1.15×10^2 (±2%)	1.16×10^2 (±1%)	1.16×10^2 (±1%)	1.16×10^2 (±2%)	1.16×10^2 (±1%)

Table 3. The contact resistivity ($\Omega.cm^2$) at different curing ages (days) of the new mortar. The curing age difference between old and new mortars was 28 days. A:plain; B:+L; C:+L+0.53 vol.% fibers; D:+L+1.1 vol.% fibers.

Old/new	1 d	3 d	7 d	10 d	14 d	20 d	24 d	28 d
A/A	$3.50x10^6$ (±10%)	$4.21x10^6$ (±11%)	$4.88x10^6$ (±9%)	$4.99x10^6$ (±8%)	$5.06x10^6$ (±7%)	$5.26x10^6$ (±6%)	$5.47x10^6$ (±7%)	$5.52x10^6$ (±5%)
A/B	$4.13x10^6$ (±9%)	$4.63x10^6$ (±8%)	$5.21x10^6$ (±7%)	$5.53x10^6$ (±8%)	$5.57x10^6$ (±7%)	$5.75x10^6$ (±6%)	$5.88x10^6$ (±7%)	$5.93x10^6$ (±6%)
A/C	$2.13x10^5$ (±4%)	$2.27x10^5$ (±3%)	$2.41x10^5$ (±2%)	$2.45x10^5$ (±3%)	$2.52x10^5$ (±2%)	$2.64x10^5$ (±2%)	$2.70x10^5$ (±1%)	$2.72x10^5$ (±1%)
A/D	$2.25x10^4$ (±3%)	$2.30x10^4$ (±2%)	$2.38x10^4$ (±1%)	$2.43x10^4$ (±2%)	$2.48x10^4$ (±1%)	$2.57x10^4$ (±2%)	$2.62x10^4$ (±2%)	$2.65x10^4$ (±1%)

the contact resistance. When resistances in all directions were considered, the dominant resistance was the new mortar's volume resistance parallel to the joint.

The addition of carbon fibers made the new mortar a viable electrical contact material. A fiber content of 1.1 vol.% resulted in lower resistances but higher material cost than a fiber content of 0.53 vol.%

The geometry-independent resistivities in Tables 2 and 3 allow contact and volume resistances to be calculated for any contact geometry and size. The resistances in turn determine the voltage required for cathodic protection. In this way, the electrical design involved with cathodic protection can be conducted in a scientific manner, so that the applied voltage will not be excessive and the electrical resistance will be minimised. As separate determinations of the contact and volume resistivities had not been previously made for any electrical contact material for cathodic protection, such electrical analysis was not possible prior to this work.

That latex addition to the new mortar increased slightly both the contact resistivity and the new mortar's volume resistivity is attributed to the high resistivity of latex (a polymer) compared to cement.

Table 4. Contact resistance for 100 cm x 100 cm joints between old and new mortars, and volume resistance of new mortar (1 cm thick) perpendicular ($\perp$) and parallel ($\parallel$) to the joint. A:plain; B:+L; C:+L+0.53 vol.% fibers; D:+L+1.1 vol.% fibers.

Old/new (56 d/ 28 d)	New mortar volume resistance (Ω)		Contact resistance (Ω)
	$\perp$	$\parallel$	
A/A	$1.83x10^1$	$1.83x10^5$	$5.52x10^2$
A/B	$3.14x10^1$	$3.14x10^5$	$5.93x10^2$
A/C	$1.41x10^{-1}$	$1.41x10^3$	$2.72x10^1$
A/D	$1.16x10^{-2}$	$1.16x10^2$	$2.65x10^0$

That curing age increase raised very slightly both contact and volume resistivities for all formulations is attributed to the hydration reaction. The very small variation with curing age makes the resistivities reported here generally applicable to essentially all curing ages. The increase of the volume resistivity with curing age is much less than that in Ref. 3.

Conclusions

Carbon fiber addition (0.53 - 1.1 vol.%) to new mortar decreased the contact resistivity between new mortar and old plain mortar, in addition to decreasing the volume resistivity of the new mortar. The contact resistivity between old plain mortar (28 days older) and new mortar (at 28 days) was 5.9×10^6, 2.7×10^5 and 2.6×10^4 $\Omega.cm^2$ and the volume resistivity at 28 days was 3.1×10^5, 1.4×10^3 and 1.2×10^2 $\Omega.cm$ at fiber contents of 0, 0.53 and 1.1 vol.% respectively, and in the presence of latex. Latex addition (without fibers) to the new mortar increased slightly both the contact resistivity between new mortar and old plain mortar and the volume resistivity of the new mortar. Both contact and volume resistivities increased very slightly with increasing curing age.

For a mortar contact material of geometry resembling that in cathodic protection, the resistance perpendicular to the contact was dominated by the contact resistance, while that parallel to the contact (due to the volume resistance of the contact material) was even larger than the contact resistance, whether or not carbon fibers or latex were present. The contact and volume resistivities allow the contact and volume resistances to be calculated and voltage design to be conducted for any geometry and size of mortar contact material for cathodic protection.

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