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ELECTRICAL CONDUCTIVITY OF PORTLAND CEMENT MORTARS

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ABSTRACT

Mortars containing volume fractions of aggregate less than 0.35 were prepared at w/c = 0.35, 0.40, and 0.45 and hydrated for 1, 14, and 28 days. Mortar electrical conductivities were determined by impedance spectroscopy, and the experimental data were fitted to the polynomial, where, σ_m is the mortar

$$\sigma_m = A + B\left(\frac{V_a}{V_m}\right) + C\left(\frac{V_a}{V_m}\right)^2 + D\left(\frac{V_a}{V_m}\right)^3$$

conductivity, V_a is the aggregate volume, V_m is the mortar volume, and A, B, C, and D are constants. Mortar electrical conductivity behavior appears to involve a competition between the insulating aggregate which lowers the mortar electrical conductivity and the development of a transition zone between the paste and aggregate which increases the conductivity. Values for the transition zone electrical conductivity were determined.

Introduction

Recently, Garboczi and co-workers (1) presented a theoretical model which described a framework to quantitatively understand the influence of the transition zone separating cement paste and aggregate on the electrical conductivity of mortar. Only one experimental study by Xie and Tang (2) has reported the parameters required to confirm the model. However, the experimental data was dismissed for two reasons. The dependence of the mortar electrical conductivities on aggregate volume fraction did not follow the expected relationship as indicated for colloidal glass suspensions (3, 4). In addition, it was felt that the fixed frequency technique used to measure the mortar electrical conductivities did not correctly eliminate the electrode-sample impedance effect resulting in low mortar electrical conductivity values (1, 5). Therefore, there is a threefold purpose to this investigation:

- To measure mortar electrical conductivities using the impedance spectroscopy technique.
- To determine the relationship between mortar electrical conductivities and aggregate volume fraction.
- To estimate the transition zone electrical conductivity.

Experimental

Type 10 Portland cement mortars were made with ASTM C109 Ottawa sand which passed #50 mesh (300 μm) and was retained on #100 mesh (150 μm). The mortars were prepared at w/c = 0.35, 0.40 and 0.45 for the compositions given in Tables 1 to 3, respectively. Subsequently, the mortars were cast into Plexiglas molds (2.54 cm × 2.54 cm × 2.54 cm) with stainless steels electrodes positioned at opposite faces to facilitate the mortar electrical conductivity measurements. Mortar electrical conductivity was determined using the impedance spectroscopy procedure and apparatus described previously (6). All mortars were cured for 1, 14 and 28 days at 100% rh.

Results and Discussion

The mortar electrical conductivities have been summarized for w/c = 0.35, 0.40 and 0.45 in Tables 1 to 3, respectively. The mortar electrical conductivities and aggregate volume fraction have been plotted for w/c = 0.35, 0.40 and 0.45 in Figures 1 to 3, respectively. For w/c=0.35, the mortar electrical conductivities increase with increasing aggregate volume fraction until the volume fraction is approximately 0.05. At aggregate volume fractions greater than 0.05, the mortar electrical conductivities decrease with increasing aggregate volume fraction. The same behavior is observed for w/c=0.40 but only for the 1 day cure. For w/c=0.40 at 14 and 28 days cure and for all the w/c=0.45 mortars, the mortar electrical conductivity decreases when the aggregate volume fraction is increased even for the dilute volume fraction aggregate range. The observations agree with the hypothesis described previously (1). That is, the mortar electrical conductivity represents a compromise between the insulating effects of the aggregate which lowers the conductivity and the development of the transition zone between the aggregate and cement paste which will increase conductivity. Therefore, for the dilute aggregate volume fractions for w/c=0.35 at all curing times and w/c=0.40 for the 1 day cure, it is the conductivity of the transition zone which predominates over the insulating effects of the aggregate. Conversely, for w/c=0.40 at 14 and 28 days cure and for w/c=0.45 at all curing times, it is the insulating property of the aggregate which is more significant than the transition zone conductivity even in the dilute aggregate volume fraction. The dependence of mortar electrical conductivity on aggregate volume fraction for the dilute aggregate volume fraction represents the first such report in the literature. The previous data did not extend to aggregate volume fractions much below 0.06 (2). When the aggregate volume fraction exceeds about 0.10 for all the mortars, the mortar electrical conductivity decreases with increasing aggregate voume fraction. The observation confirms the marked insulating influence of the aggregate at higher aggregate volume fractions.

The solid lines in Figures 1 to 3 represent the best fit of the experimental data using the Levenberg-Marquardt algorithm (7) to a polynomial of the form,

$$\sigma_m = A + B\left(\frac{V_a}{V_m}\right) + C\left(\frac{V_a}{V_m}\right)^2 + D\left(\frac{V_a}{V_m}\right)^3 \quad (1)$$

TABLE 1
Conductivities for W/C = 0.35

$\frac{V_{aggregate}}{V_{mortar}}$	σ_{mortar} $(\Omega \cdot m)^{-1}$		
	1 day	14 days	28 days
0	0.2854	0.0847	0.0700
0.0059	0.3076	0.0913	0.0720
0.0147	0.3090	0.0959	0.0771
0.0298	0.3036	0.0975	0.0779
0.0608	0.2981	0.0918	0.0719
0.0933	0.3036	0.0882	0.0673
0.163	0.2527	0.0803	0.0627
0.2389	0.2076	0.0587	0.0457
0.3229	0.1918	0.0512	0.0400

where, σ_m is the mortar electrical conductivity, V_a is the aggregate volume, V_m is the mortar volume, and A, B, C, and D are constants. The A, B, C and D constants and the multiple correlation coefficient (MCC) have been summarized in Table 4. The MCC's are generally greater than 0.98 indicating the polynomial fit of Eq.[1] to the experimental data is reasonable. The limiting slope (m_1) for aggregate volume fraction approaching zero is defined by,

$$m_1 = \left(\frac{\partial \sigma_m}{\partial \frac{V_a}{V_m}} \right)_{\frac{V_a}{V_m} \to 0} \tag{2}$$

When $m_1>0$, it is the conductivity of the transition zone between the aggregate and the cement paste which is significant. When $m_1 < 0$, it is the insulating effect of the aggregate which is significant. Therefore, m_1 values are important in characterizing the importance of the transition zone conductivity on the overall mortar electrical conductivity. Also included in Table 4 are values for m_2. These values are defined by,

TABLE 2
Conductivities for W/C = 0.40

$\frac{V_{aggregate}}{V_{mortar}}$	σ_{mortar} $(\Omega \cdot m)^{-1}$		
	1 day	14 days	28 days
0	0.4018	0.1130	0.0951
0.0137	0.4413	0.1002	0.0857
0.0278	0.4346	0.0962	0.0811
0.0568	0.4275	0.0916	0.0775
0.0873	----	0.0770	0.0654
0.1531	0.3572	0.0769	0.0657
0.2260	0.3295	0.0698	0.0601
0.3073	0.2908	0.0618	0.0520

TABLE 3
Conductivities for W/C = 0.45

$\frac{V_{aggregate}}{V_{mortar}}$	σ_{mortar} $(\Omega\cdot m)^{-1}$		
	1 day	14 days	28 days
0	0.4700	0.1520	0.1128
0.0128	0.4784	0.1384	0.1075
0.0260	0.4666	0.1338	0.1065
0.0533	0.4460	0.1303	0.1025
0.0821	0.4004	----	0.1017
0.1446	0.3553	0.1191	0.0891
0.2145	0.3331	0.1008	0.0756
0.2932	0.2934	0.0841	0.0635

$$m_2 = \frac{\left(\dfrac{\partial \sigma_m}{\partial \dfrac{V_a}{V_m}}\right)_{\frac{V_a}{V_m}=0.10}}{(\sigma_m)_{\frac{V_a}{V_m}\to 0}} \tag{3}$$

Physically, m_2 represents the slope at aggregate volume fraction equal to 0.10 normalized by the cement paste electrical conductivity. The slope was calculated at aggregate volume fraction equal to 0.10 because at aggregate volume fractions greater than 0.10 the insulating influence of the aggregate predominates for all mortars. The theoretical value of m_2 for spherical insulating inclusions in a conductive matrix is -1.50 (3). It can be seen from Table 4 that the m_2 values are not far removed from the theoretical limit. The average value for m_2 is -1.46 with a standard deviation of ±0.25 . The result means that it is possible to calculate the electrical conductivity of the mortar at any aggregate volume fraction if the paste electrical conductivity is known using the following previously derived equation (3, 4),

TABLE 4
Curve Fitting Analysis of Mortar Electrical Conductivity Data

W/C	Cure (*days*)	$\sigma_m = A + B\left(\frac{V_a}{V_m}\right) + C\left(\frac{V_a}{V_m}\right)^2 + D\left(\frac{V_a}{V_m}\right)^3$				MCC*	m_1**	m_2***
		A	B	C	D			
0.35	1	0.2855	0.8515	-9.149	17.41	0.9814	0.85	-1.60
0.35	14	0.0847	0.3507	-3.415	6.227	0.9696	0.35	-1.72
0.35	28	0.0700	0.1753	-2.072	3.846	0.9745	0.18	-1.77
0.40	1	0.4018	1.103	-11.86	23.22	0.9637	1.10	-1.42
0.40	14	0.1130	-0.6150	3.211	-5.720	0.9825	-0.61	-1.28
0.40	28	0.0951	-0.5087	2.719	-4.958	0.9858	-0.51	-1.20
0.45	1	0.4700	-0.5484	-2.153	6.840	0.9860	-0.55	-1.65
0.45	14	0.1520	-0.5778	3.104	-6.607	0.9800	-0.58	-1.02
0.45	28	0.1128	-0.1728	0.0556	-0.1521	0.9942	-0.17	-1.47

*Multiple correlation coefficient. **Eq.[2]. ***Eq.[3] .

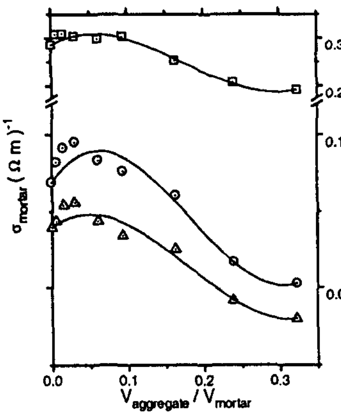

FIG. 1.
σ_{mortar} for w/c = 0.35. Curing time (days): □ = 1, O = 14, Δ = 28.

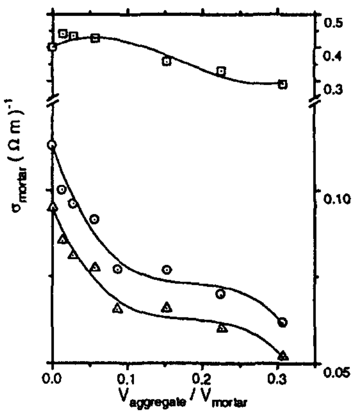

FIG. 2.
σ_{mortar} for w/c = 0.40. Curing time (days): □ = 1, O = 14, Δ = 28.

$$\sigma_m = (\sigma_m)_{\frac{V_a}{V_m}=0} \cdot \left(1 - \frac{V_a}{V_m}\right)^{\frac{3}{2}} \tag{4}$$

Interestingly, the observation also means that the transition zone electrical conductivity is not much different from the electrical conductivity of the paste. Analytical expressions for mortar electrical conductivities were derived for a hypothetical system comprising mono-size aggregate of negligible conductivity with radius b, surrounded by a transition zone of thickness h and electrical conductivity σ_z, embedded in a paste of conductivity σ_p (1). For aggregate volume fractions less than 0.05, m_1 is related to the analytical expression for the limiting slope via,

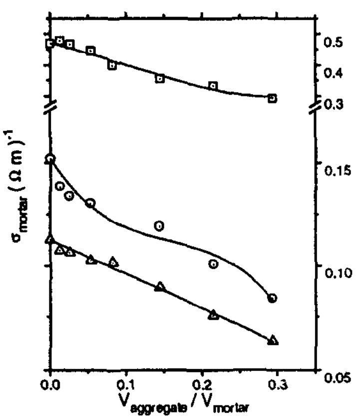

FIG. 3.
σ_{mortar} for w/c = 0.45. Curing time (days): □ = 1, O = 14, Δ = 28.

$$\frac{m_1}{\sigma_p} = 3 \cdot \frac{\left[-2\sigma_z^2 - \sigma_z\sigma_p + \left(\frac{b+h}{h}\right)^3 (2\sigma_z^2 - 2\sigma_z\sigma_p)\right]}{\left[2\sigma_z^2 + 4\sigma_z\sigma_p + \left(\frac{b}{b+h}\right)^3 (-2\sigma_z^2 + 2\sigma_z\sigma_p)\right]} \qquad (5)$$

For the 28 days cure, b=112.5 μm, h=20 μm, and for σ_p values from Tables 1 to 3, the ratio (σ_z/σ_p) was calculated as 1.014, 0.986, and 0.999 for the w/c=0.35, 0.40 and 0.45 mortars, respectively. As expected, the transition zone electrical conductivity did not differ substantially from the paste electrical conductivity.

Conclusions

- For the plot of mortar electrical conductivity versus aggregate volume fraction, the limiting slope for dilute aggregate volume fraction is related to the competition between the insulating aggregate and the conductive transition zone. When the slope>0, the former is significant.
- The mortar electrical conductivity behavior for aggregate volume fractions greater than 0.10 can be approximated by the ideal case of insulating spheres embedded in a conductive matrix.
- The transition zone electrical conductivity has about the same electrical conductivity as the corresponding cement paste for the aggregate sizes used in this investigation.

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