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ABSTRACT: Electrical conductivity measurements were made on concrete systems containing blast-furnace slag. It was found that the slag content significantly influenced the concrete conductivity. A linear relationship between the concrete conductivity and the slag content and the volume fraction of aggregate was established by experiment. The relationship can be expressed as follows

$$\sigma_c = k_a \cdot \varphi_a + k_s \cdot \left(\frac{slg}{c}\right) + k_o$$

where σ_c is the concrete conductivity; φ_a is the volumetric fraction of aggregate; (slg/c) is the relative content of slag by weight of cementitious materials; and k_a, k_s, and k_o are empirical coefficients. This relationship provides a basis for the determination of slag content in hardened concrete by electrical conductivity methods.

KEYWORDS: concrete, portland cement, blast-furnace slag, electrical conductivity

Blast-furnace slag is frequently used as a mineral admixture for concrete. Mechanical properties and durability of concrete are significantly influenced by the slag content. Accurate determination of the original mix proportions, including slag content, is often desirable for evaluation of concrete quality when the concrete does not perform as expected. Methods for the determination of cement content, aggregate content, *W-C* ratio, and so forth have been described by ASTM Standards, C 856-83, C 823-83, C 295-90, C 1078-87, C 1079-87 and C 1084-87.[3] However, there are no corresponding standards available for determination of mineral admixture content in hardened concrete.

Electrical conductivity methods (ECMs) have been developed for investigation of the microstructure of cement composites (Xie and Tang 1988; Xie et al. 1991a; Xie et al. 1991b; Xie et al. 1991c) interfacial cement chemistry (Xie et al. 1993) and the determination of aggregate content in concrete (Xie et al. 1994). A preliminary study on the application of ECM for determination of slag content in concrete is reported.

Principles of ECM for Determination of Slag Content in Concrete Systems

Physically, there are two types of electrical conduction, electronic and ionic. The former is through electronic motion in solids, the latter is principally through ionic motion in liquid. Hydrating concrete systems consist of two components, pore solution and solids, including aggregate, hydrates, and unhydrated cement. Typical values of electrical resistivity of pore solution in cement paste have been reported to be 0.25 to 0.35 Ωm (Buenfeld and Newman 1984). However, the electrical resistivities of conventional aggregates used in concrete range from 10^3 to 10^{12} Ωm (Whittington et al. 1984). Aggregates are apparently good insulators. Resistivity values are in the range 6.54 to 11.4 kΩm (Whittington et al. 1984) for air-dried portland cement paste and concrete. Values range from 25 to 45 Ωm and 10 to 13 Ωm for moist concrete and cement paste, respectively. These are an indication that dried concrete is a good insulator and that the electrical conduction through hydrating cement systems is essentially electrolytic, that is, the conduction is principally through the motion of ions, such as Na^+, K^+, OH^-, $SO_4^=$, and Ca^{2+}. The contribution from electronic conduction through solids, if any, is negligible.

Three important factors directly influence the electrical conductivity of concrete, that is, the pore solution conductivity, microstructural characteristics, and content of solid phases. Relationships between concrete conductivity and these factors have been established. For example, the concrete conductivity σ_c can be expressed empirically as follows (Xie et al. 1994).

$$\sigma_c = A_a \cdot \varphi_a + \sigma_p \tag{1}$$

where A_a is a hydration related time-dependent empirical constant; φ_a is the volumetric fraction of aggregates, fine and coarse; and σ_p is the conductivity of the cement paste in concrete. The cement paste conductivity σ_p can be expressed as follows (Xie et al. 1991b)

$$\frac{\sigma_p}{\sigma_1} = \frac{A}{1 + \left(\frac{w}{c}\right) \cdot \left(\frac{\rho_c}{\rho_w}\right)} + B \tag{2}$$

where σ_1 is the pore solution conductivity; ρ_c, ρ_w are the densities

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[3]C 856—Practice for Petrographic Examination of Hardened Concrete.

C 823—Practice for Examination and Sampling of Hardened Concrete in Constructions.

C 295—Guide for Petrographic Examination of Aggregates for Concrete.

C 1078—Test Methods for Determining Cement Content of Freshly Mixed Concrete.

C 1079—Test Methods for Determining Water Content of Freshly Mixed Concrete.

C 1084—Test Method for Portland-Cement Content of Hardened Hydraulic-Cement Concrete.

of cement and mixing water, respectively; and W-C is the water/cement ratio. A, B are coefficients dependent on hydration degree (or time) and hydrate geometry. It has been demonstrated by experiment that $A > 0$, $B > 0$, $dA/dt < 0$, and $dB/dt < 0$ (Xie et al. 1991b).

Pore solution conductivity, σ_1 depends on the type and concentration of ions in the solution and the temperature. It can be expressed by the following equation (Gu et al. 1994)

$$\sigma_1 = 10^3\,\lambda_o c - 10^3\left[\frac{a_1}{\eta(\epsilon,T)^{1/2}} + \frac{a_2}{(\epsilon,T)^{3/2}}\,\lambda_o\right]c^{3/2} \qquad (3)$$

where λ_o is the equivalent conductivity at infinite dilution $\Omega^{-1}m^2eq^{-1}$. The terms η, ϵ, are the viscosity and dielectric constant of the solvent, respectively. T is the absolute temperature. a_1 and a_2 are electrolyte type-dependent constants with values of 82.5 and 8.20×10^5, respectively for 1:1 type of electrolyte, for example, NaCl, NaOH, and so forth. c is the equivalent concentration of the solution, gram-equivalents/liter. Generally, the conductivity of an electrolytic solution increases with increasing concentration of electrolyte and solution temperature.

Influence of slag addition on the concrete conductivity is mainly through pozzolanic reaction between slag and calcium hydroxide. This reaction results in two primary changes, microstructural and chemical. Microstructurally, the pozzolanic reaction is always accompanied by the formation of C-S-H gel, which changes the content of solid phases and pore structure. Chemically the pozzolanic reaction reduces the ionic concentration in the pore solution, especially that of Na^+, K^+, OH^-, and Ca^{2+}. These changes are reflected in the conductivity change. The extent of the influence of slag addition on the conductivity depends on the slag content. Preliminary experimental results based on an application of electrical conductivity methods to the determination of slag content in hardened concrete are reported.

Experimental

Materials

Type 10 Canadian standard portland cement was used. The chemical composition (wt %) is as follows: CaO, 61.21; SiO_2, 19.83; Al_2O_3, 4.18; Fe_2O_3, 3.20; MgO, 4.09; SO_3, 3.93; K_2O, 0.82; and Na_2O, 0.45. The chemical composition (wt %) of the slag used is as follows: CaO, 36.94; SiO_2, 35.3; Al_2O_3, 10.62; Fe_2O_3, 0.58; MgO, 13.32; and SO_3, 1.41.

Construction sand and limestone from Ottawa area were used as fine and coarse aggregates.

Specimen Preparation

Twenty different concretes were prepared. Four (cement + slag):sand:aggregate mass ratios (1:1:1, 1:1.5:1.5, 1:2:2, and 1:2.5:2.5) and five different slag/(cement + slag) ratios (0, 15, 30, 45, and 60%) were used. Fresh concrete mixtures were mixed in a Hobart mixer at a water/(cement + slag) ratio of 0.45 and cast in electrical conduction cells with dimensions of 8 by 8 by 4 cm. The distance between the electrodes is 4 cm; the area of the electrodes is 8 by 8 cm. The samples were cured in a 100% relative humidity (RH) environment at 22 ± 1°C. At designated hydration times, electrical resistance measurements were made for each sample.

Resistance Measurement

Resistance measurement was carried out with a computer-controlled data acquisition system. The principles for resistance measurement are described in detail elsewhere (Xie et al. 1991a; Xie et al. 1991c). The electrical conductivity σ_c of the specimen is calculated by the following equation

$$\sigma_c = \frac{L}{S}\cdot\frac{1}{R} \qquad (4)$$

where L, S are the distance between the electrodes and the electrode area, respectively. R is the measured resistance.

Results and Discussion

Concrete Conductivity-Hydration Time

Change of concrete conductivity with hydration time is presented in Fig. 1. Typical characteristics are observed for each conductivity versus hydration time curve, that is, a dramatic conductivity change takes place only at early hydration times. Conductivity values are relatively constant at later hydration times, especially after 1 to 2 months. Therefore, only conductivity values at later hydration times are useful for the determination of slag content. The electrical conductivity method for determination of phase composition is effective only for mature concrete.

Relationship Between Concrete Conductivity and Aggregate Content

Conductivity versus volumetric fraction of both fine and coarse aggregate for the systems containing different amount of slag is plotted in Fig. 2.

It is evident from Fig. 2 that Eq 1 is applicable for both the concrete without slag (Xie et al. 1994) and concrete with different slag content. These results indicate that aggregate content has significant influence on the concrete conductivity. Therefore, when electrical conductivity methods are employed for determination of slag content, aggregate content must be known. Aggregate content determination can be made according to the prevailing ASTM Standards.

Effect of Slag Content on Concrete Conductivity

Concrete conductivity is plotted in Fig. 3 versus slag/(cement + slag) ratio for the systems with different sand/(cement + slag) ratios and coarse aggregate/(cement + slag) ratios.

It can be seen that the conductivity of concrete is proportional to the slag/(cement + slag) ratio at all hydration times. It is noted from Fig. 3 that the conductivity increases with increasing slag/(cement + slag) ratio at 1 day of hydration and decreases after 3 days. This can be explained as follows. At 1 day of hydration, the extent of pozzolanic reaction is low and the system with higher slag content has a relatively lower content of cement and quantity of hydration products. The system has higher porosity and hence a higher conductivity value. The effect of pozzolanic reaction on the microstructure and pore solution chemistry is more significant at later ages. The reaction produces more C-S-H gel and results in a low ionic concentration in the pore solution. Lower conductivity values for the system with higher slag content result.

The linear relationship between the concrete conductivity and slag/(cement + slag) ratio indicates that the electrical conductivity

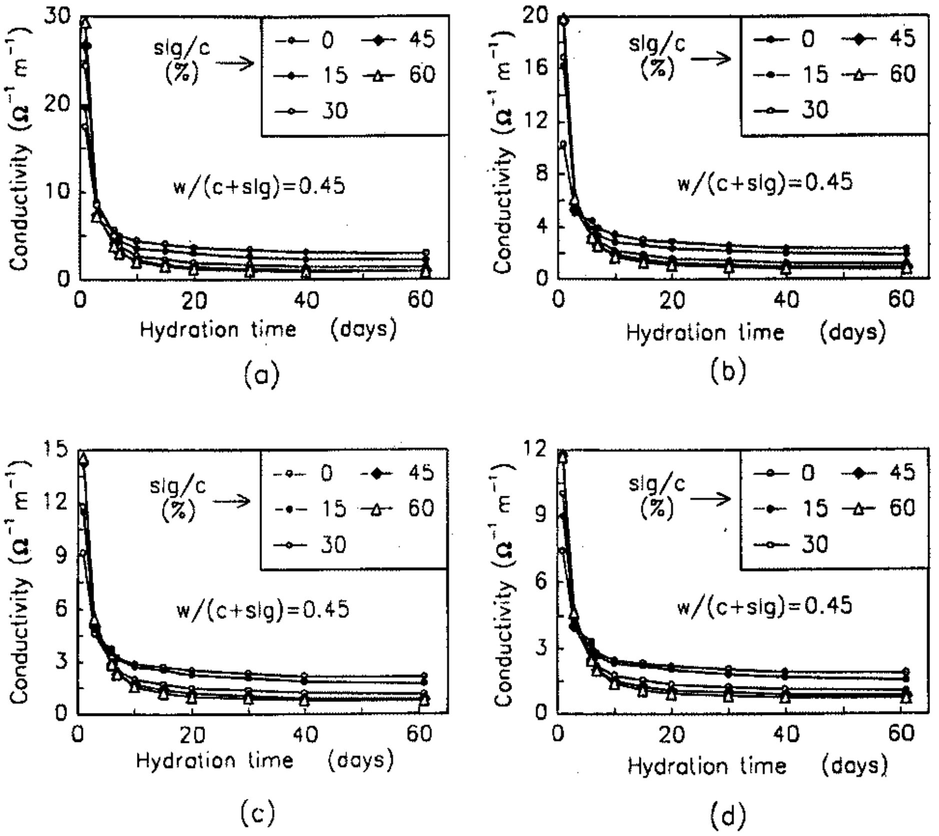

FIG. 1—*Concrete conductivity versus hydration time;* (a) *mix 1:1:1;* (b) *mix 1:1.5:1.5;* (c) *mix 1:2:2;* and (d) *mix 1:2.5:2.5.*

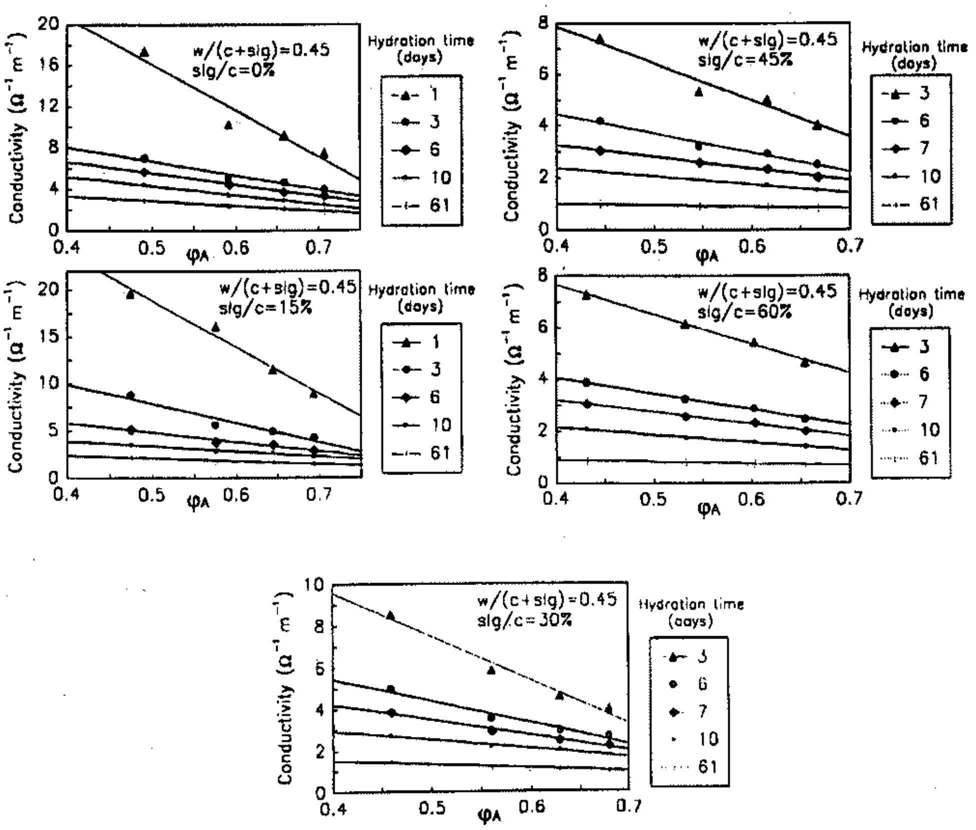

FIG. 2—*Concrete conductivity versus volumetric fraction of aggregate.*

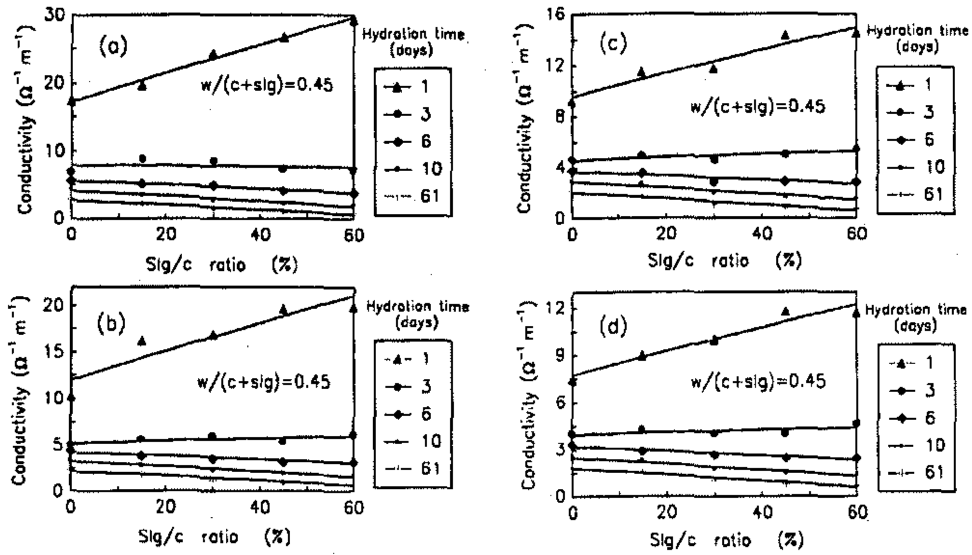

FIG. 3—*Concrete conductivity versus slag/(cement + slag) ratio.* (a) *mix 1:1:1;* (b) *mix 1:1.5:1.5;* (c) *mix 1:2:2; and* (d) *mix 1:2.5:2.5.*

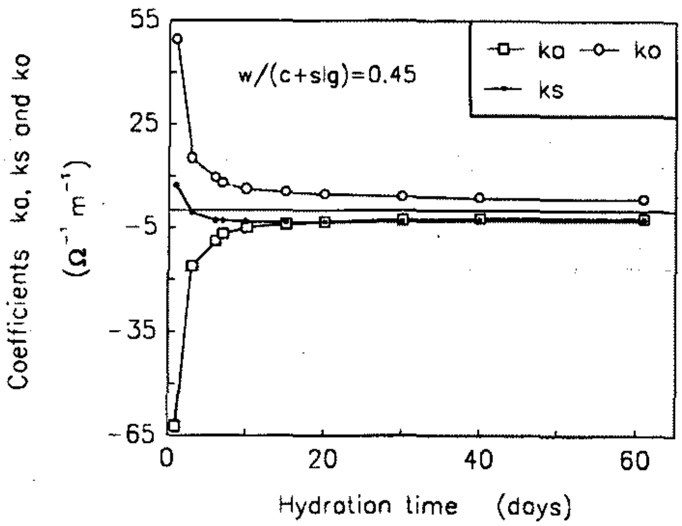

FIG. 4—*Correlation coefficients in Eq 5 versus hydration time.*

TABLE 1—*Empirical coefficients in Eq 5.*

Hydration Time, (days)	k_a, $\Omega^{-1}\cdot m^{-1}$	k_s, $\Omega^{-1}\cdot m^{-1}$	k_o, $\Omega^{-1}\cdot m^{-1}$	Correlation Coefficient
1	−62.23	7.24	49.69	0.926
3	−16.13	−0.785	15.27	0.941
6	−8.94	−2.85	9.67	0.970
7	−6.84	−2.91	7.86	0.956
10	−4.87	−3.25	6.18	0.953
15	−3.97	−3.48	5.41	0.953
20	−3.30	−3.48	4.77	0.952
30	−2.67	−3.16	4.14	0.950
40	−2.29	−2.96	3.70	0.948
61	−2.15	−2.82	3.50	0.948

method may be a simple and effective tool for the determination of slag content in hardened concrete.

Correlation of Conductivity-Slag/(Cement + Slag) Ratio-Aggregate Volume Fraction

The previous results indicate that the concrete conductivity is proportional to both volumetric fraction of aggregate and slag/(cement + slag) ratio at each hydration time. Therefore, it is useful to combine these variables in a single equation in the following form

$$\sigma_c = k_a \cdot \varphi_a + k_s \cdot \left(\frac{slg}{c}\right) + k_o \qquad (5)$$

where k_a, k_s, and k_o are three empirical coefficients that can be obtained by applying the least-square method to the experimental data. The results are listed in Table 1 and plotted in Fig. 4. The correlation coefficient for most of the empirical equations is ≥ 0.95. This indicates that Eq 5 is useful for correlating conductivity to φ_a and slg/c. The coefficient, k_o, in Eq 5 has a definite physical meaning. It represents the conductivity of the system with $\varphi_a = 0$ and $slg/c = 0$; that is, cement paste with the same *W-C* ratio.

Application of Eq 5 provides a means for the determination of slag content in hardened concrete by electrical conductivity methods. The relative content of slag-to-cementitious materials can be obtained through simple conductivity measurement if the aggregate content is known.

It should be mentioned that a fixed water/(cement + slag) ratio 0.45 was used in this work. Additional experiments with different water/(cement + slag) ratios are required to establish a more complete empirical equation.

Conclusion

There is a simple linear dependence between conductivity of mature concrete and aggregate and slag content. It forms a basis for the determination of slag content in hardened concrete by electrical conductivity methods.

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