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Electrical conductivity of granulated slag cement kiln dust–silica fume pastes at different porosities

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Abstract

Blended cement pastes containing granulated slag, cement kiln dust (CKD), made with and without silica fume, were prepared using the initial water-to-solid (w/s) ratios of 0.30, 0.40, and 0.50 to produce low-normal and high-porosity pastes, respectively. The variations of electrical conductivity with hydration time were measured at 30°C and 50°C for each paste during setting and hardening processes after gauging with deionized water. The results of this study demonstrate that the electrical response characteristics of setting pastes can be used as an effective means of studying the progress of blended cement hydration and also for monitoring structural changes occurring within the paste, as well as, reflecting the hydraulic reactivity of granulated slag and silica fume as pozzolanic constituents of the hardening pastes. © 2001 Elsevier Science Ltd. All rights reserved.

Keywords: Electrical properties; Granulated blast-furnace slag; Silica fume; Cement kiln dust; CKD

1. Introduction

The pozzolanic addition reduces the heat of hydration and improves the durability of cements. The pozzolanic material (silica fume) showed an improving of the microstructure of cement paste in concrete by densifying the cement paste matrix [1–4]. The addition of silica fume to ordinary Portland cement leads to the consumption of $Ca(OH)_2$ obtained during cement hydration as a result of interaction with active silica fume to form the CSH phases [5,6]. The relations between electrical conductivity and setting characteristics as well as structural changes of the hardened pastes, made with and without silica fume, were reported in the literature [7]. The variations in electrical conductivity of slag cement and slag–lime pastes, as an indication for the mechanism of cementing action during the early stages of hydration, were also studied [8]. Recent studies [9] showed the influence of silica fume replacement of cement on expansion and drying shrinkage. Also, the effect of fly ash and silica fume on compressive strength and fracture of concrete was reported [10]. In other studies, the electrical conductivity and resistivity measurements were used to follow the stages of cement hydration [11–13].

This paper deals with the effect of some variables, namely, water-to-solid (water/solid) ratio, silica fume content, and temperature, on the electrical conductivity of the hardened blended pastes. All testes reported here were made during the processes of setting and hardening and measured at a relatively low AC frequency (1000 Hz); this means that the changes in electrical conductivity can be attributed to changes in the number and/or the mobility of charge carrying ions.

2. Experimental

The granulated blast-furnace slag, having a Blaine surface area 3200 cm^2/g, raw (unwashed) and washed cement kiln dust (CKD) having a Blaine surface area 3350 cm^2/g used in this study, were provided by Helwan Portland Cement Company, Egypt. The washed CKD was made by washing raw CKD with distilled water (water/CKD weight ratio = 4:1) for 3 min using a mechanical stirrer, filtered off, and washed several times, dried at 105°C for 2 h. Condensed silica fume having a specific surface area of 20 m^2/g

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Table 1
The chemical oxide composition of starting materials (wt.%)

Material	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	Na_2O	K_2O	Cl	L.O.I.
Granulated slag	32.44	15.45	2.04	36.20	4.98	0.64	1.00	1.40	0.07	–
Raw CKD	14.37	3.97	4.49	51.07	2.40	4.43	1.55	1.20	2.95	18.85
Washed CKD	14.86	3.77	4.51	68.55	3.39	4.44	–	0.61	1.27	18.15
Silica fume	95.50	0.70	1.90	–	–	0.70	–	–	–	1.00

was also used. The chemical oxide composition of these materials are given in Table 1.

Five dry mixtures were prepared using slag: CKD (raw or washed) of 80:20 (by weight) and containing 0%, 2%, 5%, 10%, and 20% active silica fume as a partial substituent of slag. For conductivity measurements, the blended cement pastes were made with different initial porosities using the w/s ratios of 0.30, 0.40, and 0.50 by weight. Mixing with deionized water was carried out for 3 min continuously. Each paste was then transferred to a cylindrical plastic sample holder (15 mm internal diameter) with stainless steel electrodes at both sides with 12 mm distance between them and the cell was kept in humidity cabinet at 100% relative humidity during the test period. The changes in the electrical conductivity for each paste were measured at time intervals from 3.5 min up to 24 h (during setting and hardening processes) at two constant temperatures of 30°C and 50°C.

3. Results and discussion

3.1. Electrical conductance of blended cement pastes made of granulated slag and raw CKD with and without silica fume

The electrical conductivity curves for the various blended cement pastes made of granulated slag and raw (unwashed) CKD with and without silica fume by using the w/s ratios of 0.30, 0.40, and 0.50 are shown in Figs. 1 and 2 for the specimens hydrated at 30°C and 50°C, respectively. Obviously, all the conductograms shown in Figs. 1 and 2 exhibit only one conductivity maximum. In all cases investigated, the increase of electrical conductivity in the initial stage of hydration is mainly attributed to the initial hydrolysis of the raw CKD; a result that might be associated with the increase of ionic concentration and mobility of ions (Ca^{2+}, OH^-, Na^+, and K^+) [4,7,14]. These ions are, however, readily absorbed by the formation of a thin layer of hydration products, which form an envelop around the unhydrated slag and CKD grains. This envelop consists of electrical double layers of adsorbed Ca^{2+}, Na^+, and K^+ ions and counter-ions that lead to a decrease in both of the number and mobility of ions, and consequently, to that of the conductivity values after the maximum.

The addition of silica fume as a partial substituent of granulated slag affects the initial conductivity values as well as the location of the conductivity peaks. There appeared a notable increase in the rate of initial hydrolysis of CKD with increasing addition of silica fume, a result that is clearly distinguished from the increased initial conductivity values at the first few minutes of hydration. In addition, the slight shift of the conductivity peaks to longer times of hydration with increasing silica fume content is actually due to the retardation effect on slag hydration as a result of the high hydraulic reactivity of silica fume (as compared with granulated slag) forming a sort of coating around slag grains during the early stages of the hydration process.

Obviously, by increasing the w/s ratios from 0.30 up to 0.50 the conductance increases and the location of the conductivity peaks of the higher w/s pastes appear at somewhat later hydration times than those of the conductograms obtained for the lower w/s ratio (0.30) pastes. This is attributed to the increase of the degree of the hydrolysis of the raw CKD constituents by increasing the w/s ratio of the paste, i.e., leading thereby to an increase in the number of ions and consequently to that of the intensity of the conductivity maxima.

When hydration takes place at 50°C (Fig. 2), the values of the maxima of the conductograms obtained for the various blended cement pastes are shifted to higher siemens values and the location of the maxima are shifted to shorter time values. Evidently, the increase in the temperature of hydration leads to an increase in the rate of hydrolysis of CKD, i.e., increase of ions, which is associated with an increase in the conductivity values. Moreover, the location of the conductivity peaks occurred at shorter times with increasing rate of hydration. In addition, there appeared a marked decrease in the conductivity values after the maxima in the conductograms at the later hydration ages; this result is mainly associated with the increased rate of formation of hydration products leading to a marked consumption of ions during the activated effect of slag hydration at a higher temperature.

3.2. Electrical conductance of blended cement pastes made of granulated slag and washed CKD with and without silica fume

Figs. 3 and 4 illustrate the conductivity curves for the different blended cement pastes made of slag and washed CKD with and without active silica fume by using w/s ratios of 0.30, 0.40, and 0.50 for specimens hydrated at 30°C and 50°C, respectively. Evidently, a notable lowering in the conductivity maxima of the pastes made of washed CKD (Figs. 3 and 4) is observed as compared with the pastes made of raw CKD (Figs. 1 and 2). This result is mainly attributed to the reduction of alkali contents (Na^+ and K^+ ions) in washed CKD, which leads to a decrease in the rate

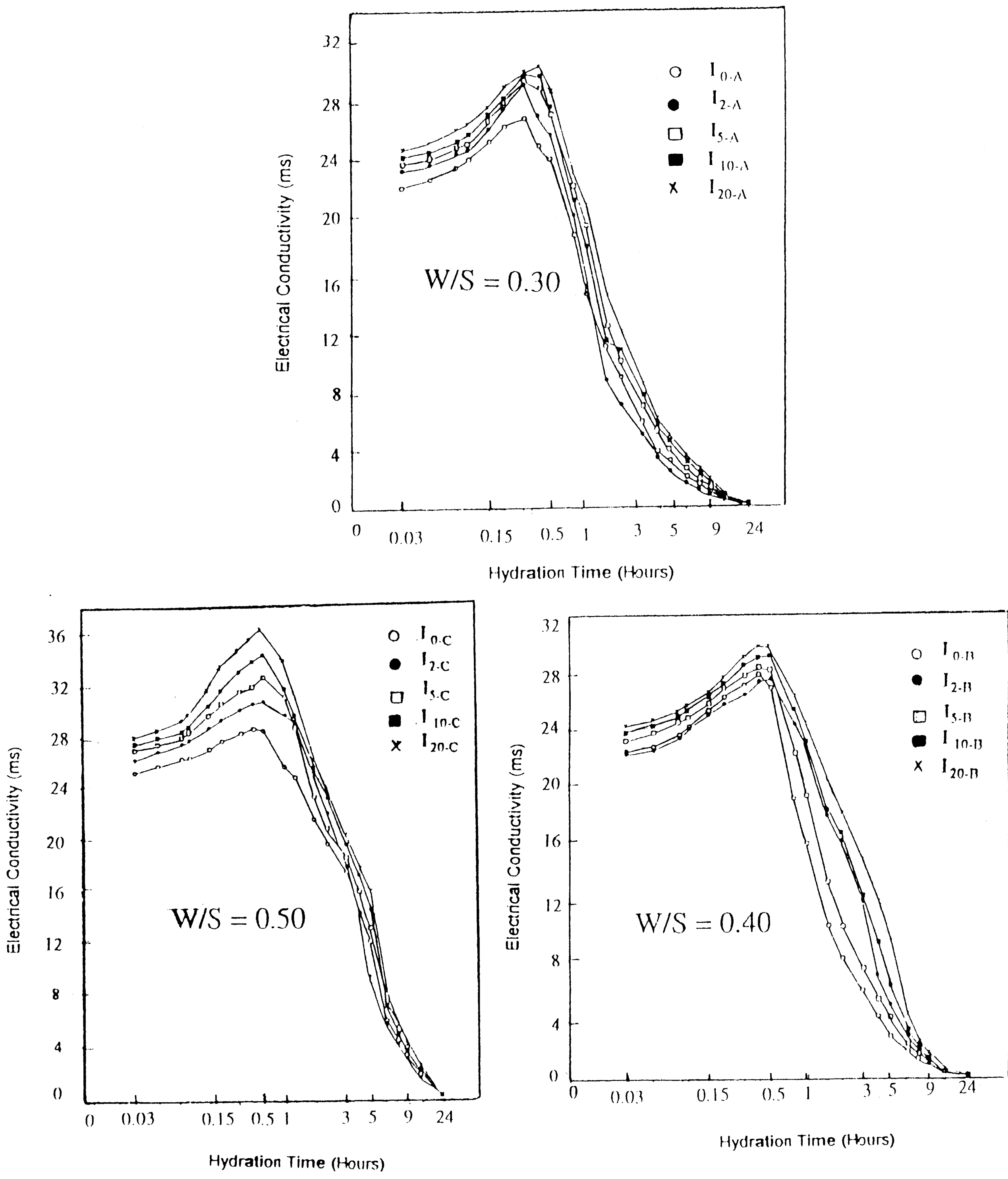

Fig. 1. Electrical conductivity–time curves of different blended cement pastes of Mixes I_{0-A}–I_{20-A}, I_{0-B}–I_{20-B}, and I_{0-C}–I_{20-C} using (w/s) ratios of 0.30, 0.40, and 0.50, respectively, at 30°C.

of its initial hydrolysis. Also, the rate of decrease in the conductivity values with time of hydration beyond the maxima is less in the pastes made of washed CKD than those of the pastes made of raw CKD. This result is mainly due to the decreased rate of activation of granulated slag and silica fume by the washed CKD as compared with the pastes made with raw CKD.

By increasing the w/s ratio of the pastes from 0.30 up to 0.50, the degree of hydrolysis of the washed CKD constituents increases leading thus to an increase in the number of

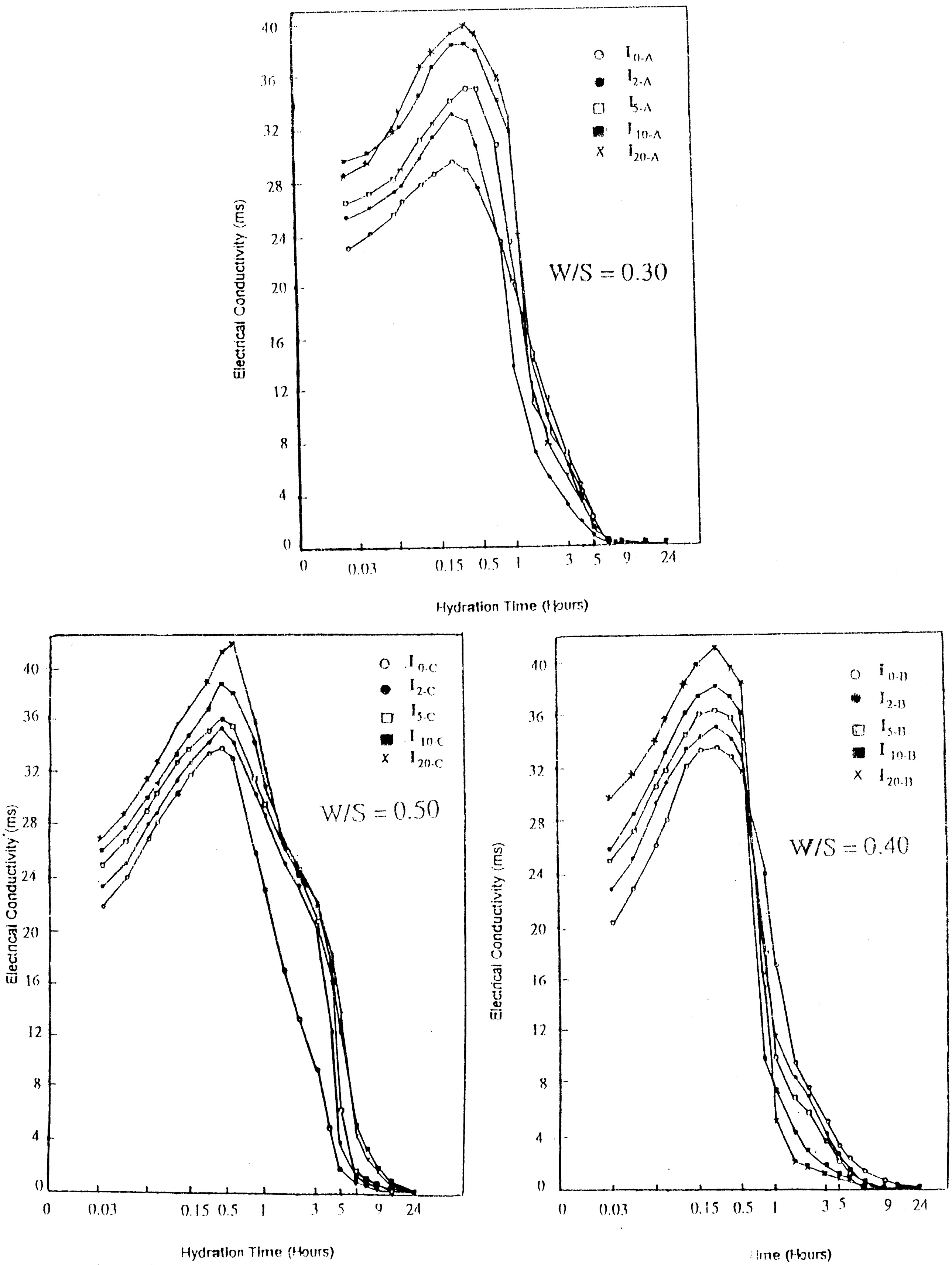

Fig. 2. Electrical conductivity–time curves of different blended cement pastes of Mixes $I_{0\text{-}A}$–$I_{20\text{-}A}$, $I_{0\text{-}B}$–$I_{20\text{-}B}$, and $I_{0\text{-}C}$–$I_{20\text{-}C}$ using (w/s) ratios of 0.30, 0.40, and 0.50, respectively, at 50°C.

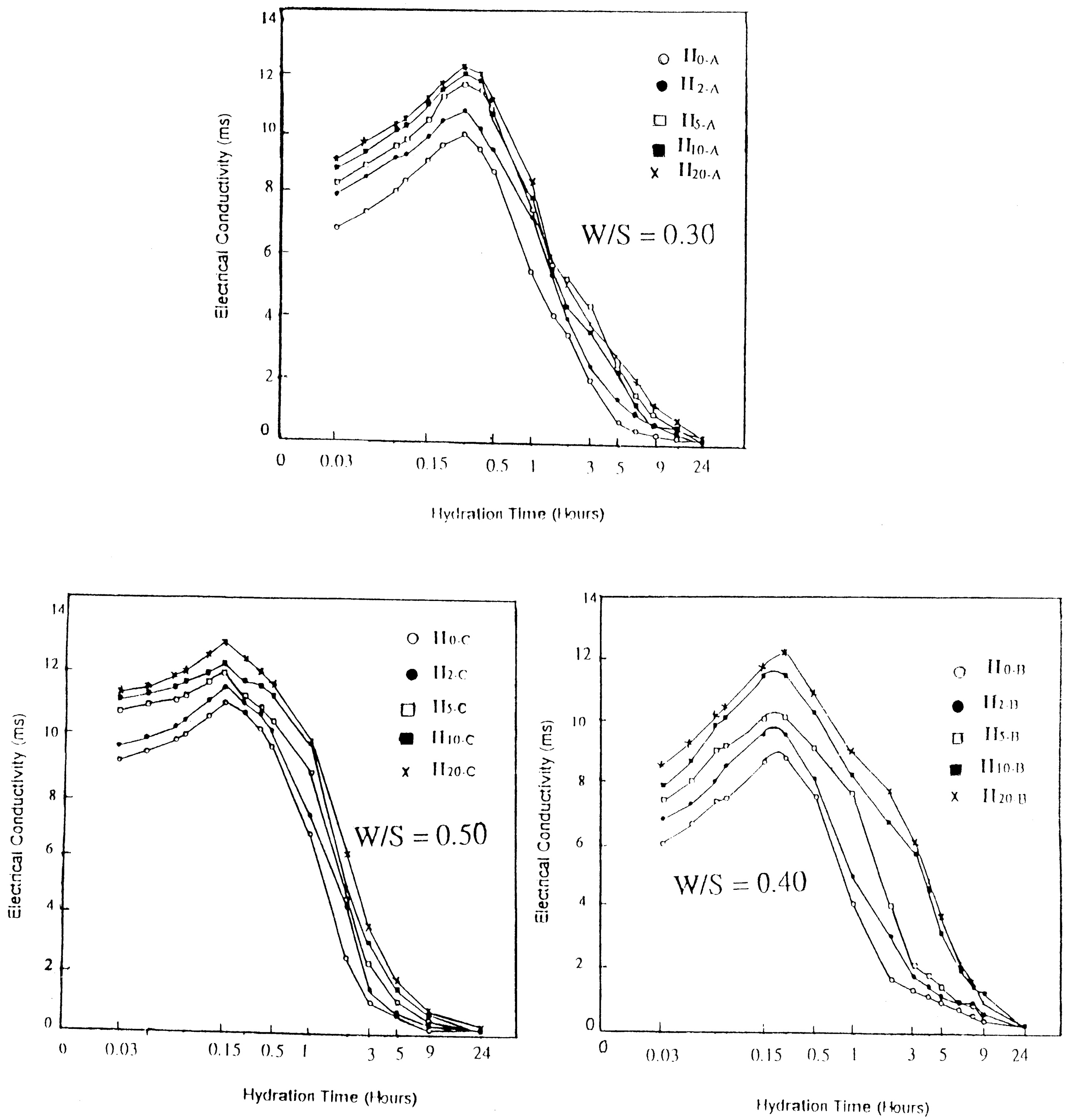

Fig. 3. Electrical conductivity–time curves of different blended cement pastes of Mixes $II_{0\text{-}A}$–$II_{20\text{-}A}$, $II_{0\text{-}B}$–$II_{20\text{-}B}$, and $II_{0\text{-}C}$–$II_{20\text{-}C}$ using (w/s) ratios of 0.30, 0.40, and 0.50, respectively, at 30°C.

ions and consequently facilitate the pozzolanic interaction of slag and silica fume with the liberated free $Ca(OH)_2$ during CKD hydration. This accounts for the shortening of the time required for the conductivity peaks to develop with increasing w/s ratio of the paste. However, the conductance values as well as the location of the conductivity peaks are slightly affected upon increasing the w/s ratio.

The effect of increasing the hydration temperature to 50°C on the electrical conductivity values of the blended cement pastes are demonstrated in Fig. 4. Evidently, all the conductograms show the same trend as those obtained for the specimens containing unwashed CKD hydrated at 50°C (Fig. 2), owing to the same reasons discussed earlier in this investigation.

4. Conclusions

The main conclusions derived from this study may be summarized as follows.

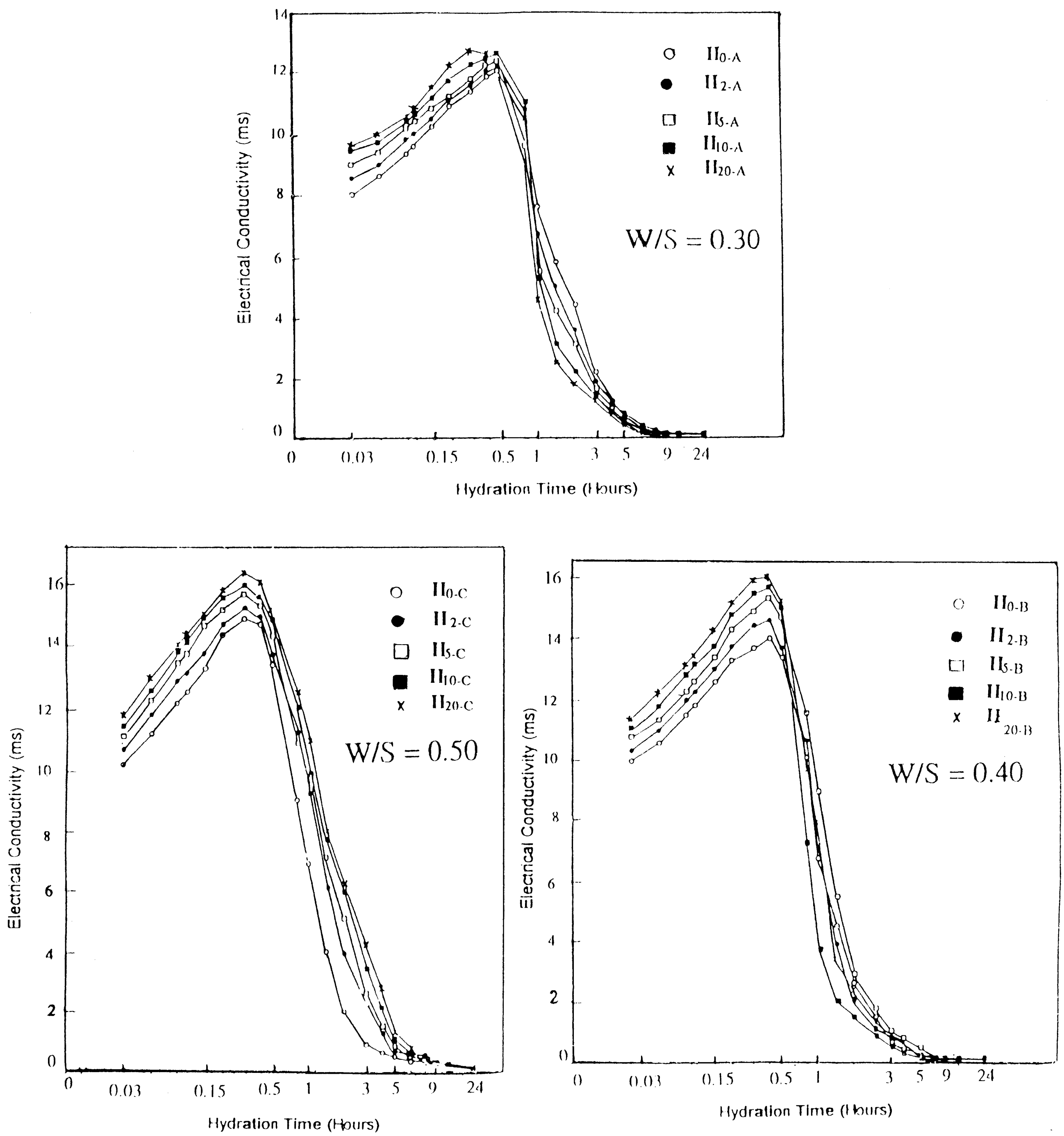

Fig. 4. Electrical conductivity–time curves of different blended cement pastes of Mixes $II_{0\text{-}A}$–$II_{20\text{-}A}$, $II_{0\text{-}B}$–$II_{20\text{-}B}$, and $II_{0\text{-}C}$–$I_{20\text{-}C}$ using (w/s) ratios of 0.30, 0.40, and 0.50, respectively, at 50°C.

1. The changes in electrical conductance reflect the physical and chemical changes taking place in the blended cement paste and can be used as an indication for the setting characteristics of the hardened pastes.

2. Addition of silica fume leads to an increase in the initial conductivity values as well as a shift of the conductivity peaks to longer times of hydration; this effect is mainly related to the relatively high hydraulic reactivity of silica fume as compared with granulated slag.

3. By increasing the porosity of the paste (as controlled by the initial w/s ratio), the conductivity increases; a result that is mainly attributed to the increase of the degree of hydrolysis of CKD constituents leading to an increased number of charge carriers.

4. The electrical conductance increases with increasing hydration temperature up to 50°C, as the degree of initial hydrolysis of cement blend increases at higher temperatures.

5. The hydraulic reactivities of granulated slag and silica fume as activated by raw CKD is relatively high as compared with those activated by washed CKD; this result is due to the presence of excess alkali contents in raw CKD.

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