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Influence of aggregate fraction in the mix on the reliability of the rapid chloride permeability test

T.H. Wee, Arvind K. Suryavanshi* San San Tin

High Performance Concrete Group, Civil Engineering Department, National University of Singapore, Singapore 119260

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Abstract

The present paper elucidates the influence of aggregate content of the mix on the reliability of rapid chloride permeability test (RCPT) results. For this purpose, test specimens prepared with mixes varying in total aggregate content were subjected to soaking test, RCPT and electrical resistivity measurements, and the results from these tests were compared and conclusions drawn. The RCPT results indicated the plain cement concrete to be relatively more resistant against chloride penetration than the plain cement mortar, whilst the opposite was true according to the 90-day soaking test results. The above trend did not change despite the addition of silica fume (SF) to the concrete and mortar mixes. The lower aggregate content or higher paste content of plain cement mortar and the mortar with SF is shown to mislead the RCPT results. The higher paste content in the above mix promotes the conduction of higher charge as a result of lower electrical resistivity. Thus the results derived from the present investigation emphasize the need to consider the volume fraction of aggregate in the mix with and without SF while interpreting the RCPT results. Furthermore, regardless of the total aggregate and SF content in the mix, the total charge passed (from the RCPT) through the mix decreased exponentially with increasing electrical resistivity. On the other hand, for those mixes containing either SF or a high volume fraction of aggregates the linear correlation between the total charge passed and chloride penetration coefficient (K) was poor. However, for the mix with relatively lower aggregate content and with no SF the charge passed was well correlated linearly with K. © 1999 Published by Elsevier Science Ltd. All rights reserved.

Keywords: Rapid chloride permeability test; Aggregate content; Silica fume; Electrical resistivity; Soaking test

1. Introduction

The exposed surfaces of concrete structures are subjected to the attack of deleterious agents such as temperature, wind, sun, moisture, chlorides and atmospheric carbon dioxide. It is these deleterious agents that are instrumental in causing the rapid deterioration of concrete structures, sometimes leading to premature failure. Therefore, it is vital to focus attention on those properties of the concrete near the exposed surface, which allow the ingress of deleterious agents.

The important properties of concrete present near the exposed surface which need attention are adsorption, gas diffusion and capillary absorption when the concrete is in an unsaturated state, and permeability and diffusion when the concrete is in a saturated or nearly saturated state. Submerged concrete structures are generally devoid of dissolved oxygen, and therefore, are free from chloride-induced corrosion of the reinforcing steel. However, in above-ground concrete structures, the exposed concrete surface will be subjected to drying action due to wind, temperature and sun. Thus, the concrete near the exposed surface will have non-uniform moisture distribution (or moisture gradients), and the moisture content generally will be lower than the saturation limit [1]. As a result of the exposed concrete being in an unsaturated state, moisture (with chlorides and dissolved oxygen) will be absorbed into the concrete cover by capillary forces depending on the degree of saturation of the concrete, thereby sustain the chloride-induced corrosion of the reinforcing steel. The movement of moisture containing chloride and dissolved oxygen by capillary absorption is reported to be significantly faster, which

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*Corresponding author. Fax: 0065-7791-635; E-mail; cveas@nus.edu.sg

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demonstrates the significance of capillary absorption for the long-term durability of above-ground concrete structures [1–3]. However, under atmospheric pressure, once the exposed concrete becomes saturated with moisture due to capillary absorption, then diffusion becomes the principal mode of chloride and oxygen transportation into the concrete cover. Incidentally, in the bulk concrete (away from exposed concrete) of above-ground structures, diffusion will be the principal mode of chloride and oxygen transportation. Fluid flow (permeability) through the concrete will commence only when the pressure head exceeds the atmospheric pressure.

Studies on absorption of moisture (sorptivity) by a hardened cement matrix have been performed by various types of tests, and these tests are based on the principle of monitoring the volume of water absorbed by the matrix over a known period of time [1]. Studies on chloride diffusion are performed by tests assuming either steady-state flow (thin cement disc specimens) or non-steady-state (concrete specimen) flow across the specimen. The steady-state chloride diffusion tests which are performed by using diffusion cells are time-consuming and are also unrealistic as cement paste specimens instead of concrete specimens are used. The soaking, ponding and cyclic wetting and drying tests in which non-steady-state chloride flow across the specimen is simulated are also time-consuming, but are ideal for long-term studies. As the non-steady-state chloride diffusion tests are time-consuming, attempts were made to accelerate the chloride diffusion through the small representative specimens by imposing an external electric field such as in the rapid chloride permeability test (RCPT) T277-89 proposed by the American Association of State Highway and Transportation Officials (AASHTO) [4].

In the RCPT, the total charge passed through the hardened cement matrix over a known time interval is measured, and is then related to the chloride permeability by using the established relationships between the chloride permeability and the total charge passed [5]. It is reported that the RCPT results showed good correlation with the results of 90-day chloride ponding tests on companion slabs cast from the same concrete mix [4]. The higher the total charge passed through the hardened cement matrix, the lower is its resistance to chloride penetration. In recent years, the RCPT is widely employed for the qualitative evaluation of chloride permeability of structural concrete although the technique has a few drawbacks. The main drawback of the RCPT according to Andrade [6] is the possibility of other ions present in the pore solution of the hardened matrix conducting a part of the total current leading to an inaccurate estimation. Furthermore, the electrical potential applied across the specimen heats up the specimen, and as a result of this, the chloride transportation is significantly accelerated, and therefore leads to erroneous conclusions [7]. In addition, the mechanism of electric conduction through cement-based materials is mostly electrolytic in nature and is through the cement paste owing to the infinitely large electrical resistivity of the aggregates [8]. Thus, the aggregates, depending on their volume fraction in the mix and type, may also influence the RCPT results, although no data have been reported in the published literature. The above discussion calls for an in-depth assessment of the reliability of the RCPT as a test method to predict the chloride permeability of structural concrete.

The present paper elucidates the influence of the total aggregate content of the mix on the reliability of RCPT results. For this purpose, test specimens prepared with mixes differing in total aggregate (fine+coarse) content were subjected to soaking test, RCPT and electrical resistivity measurements. The results of these tests were compared and conclusions drawn.

2. Experimental work

The first stage of the experimental work consisted of generating data on the depth of chloride penetration through the test specimens. These data were generated through the soaking test, in which the test specimens were immersed in a salt solution of known chloride concentration for a fixed interval (90 days). After completion of the exposure period the depths of chloride penetration were estimated. The soaking test was employed because it simulates the time-dependent chloride intrusion process similar to that in field concrete structures exposed to marine environment. The data on depth of chloride penetration thus generated through the soaking test were used as the reference data for the purpose of comparison. In the second stage, the data on total charge passed obtained from the RCPT were compared with the depth of chloride penetration. The electrical resistivities of test specimens were also measured in order to supplement the experimental results.

2.1. Background

Since the objective of the study is to investigate the role of aggregate fraction on the reliability of RCPT results, care was taken to design appropriate mixes for the study. The electrical resistivities of silica sand (fine aggregate) and granite (coarse aggregate) are in the range of 3.8×10^4–1.2×10^{12} Ω m and 5×10^3–1×10^6 Ω m respectively [8]. By considering the above resistivity ranges for silica sand and granite, it is possible that there can be a silica sand and granite of nearly identical resistivity depending upon their mineralogy and source. Given the above possibility, and not knowing the precise resistivities of fine and coarse aggregates as their sources were varying from time to time, it was decided not to use normal concrete mixes (similar to the field mixes) of similar water–binder (w/b) ratios with varying fine and coarse aggregate contents. This was because the desired effect due to varying fine and coarse aggregate (of nearly identical resistivities) content on RCPT results, which is believed to be small to detect, is not overlapped by the dominant heterogeneity effects, unless it is ensured that the resistivities of coarse and fine aggregates are widely different. This also rules out employing concrete and mortar mixes of similar w/b ratios and aggregate fractions as the resistivities of both concrete and mortar in the hardened state may be close to each other. Hence, in the present investigation, as there was no information on the resistivity of the fine and coarse aggregates, and the source of aggregates was also varying with time, it was decided to use concrete and mortar mixes differing widely in total aggregate contents.

During the RCPT, the test specimen is liable to heat up (the Joule effect) due to the applied electrical potential (60 V), and as a result of the temperature rise, ionic migration through the specimens will be further accelerated leading to faulty results [7]. The hardened cement matrix with a porous microstructure has a greater tendency to heat up (higher temperature rise) due to the large current flow compared to the hardened cement matrix with a relatively dense pore structure [7]. Furthermore, no scientific data are available in the published literature on the influence of aggregates on the Joule effect. Therefore, based on the existing knowledge it was decided to maintain a higher cement content in both concrete and mortar mixes to minimize the influence of the Joule effect on the RCPT results. However, the cement content of concrete mixes cannot be maintained like that of the mortar of similar w/b ratios because of the need to accommodate the coarse aggregates in the former. By considering the physical dimensions of the specimens used in the RCPT, soaking and electrical resistivity tests (see next section), the chances of the concrete and mortar specimens cracking due to thermal effects (differential temperature gradients) as a result of higher cement content are remote. The influence of aggregate–cement paste transition zones on RCPT results is not taken into consideration as no evidence exists in the published literature to support its influence on RCPT results. Furthermore, in well-cured concrete (see next section for curing details) the influence of aggregate–cement paste transition zones will be negligible [9]. The above is also true for the concrete mixes blended with silica fume (SF) as the SF particles, because of their small size, are known to fill the aggregate–paste transition zones more effectively.

Thus, in the present investigation more controlled mixes are used with the aim of understanding the role of the aggregate content on the RCPT results. The present study resembles numerous other studies published in the literature which have been carried out under controlled conditions with the aim of understanding the mechanism; for example, studies carried out using neat cement paste specimens instead of concrete specimens.

2.2. *Test specimens*

In the present investigation, apart from the plain cement concrete and mortar mix, concrete and mortar mixes blended with SF were also used. When the test specimens were prepared with the plain cement concrete and mortar, mixes of three different w/b ratios of 0.40, 0.50 and 0.60 were employed. However, the total aggregate (fine+coarse) content (kg m^{-3}) of the plain cement concrete mix, as explained earlier, was deliberately kept much higher than the corresponding mortar mixes of similar w/b ratio. When the test specimens were prepared with concrete and mortar mixes containing SF, the w/b ratio of the mix was maintained at 0.50. The total aggregate content of the concrete mix blended with SF was deliberately kept higher than the mortar mix blended with SF. SF was added to the mix by replacing ordinary portland cement (OPC) at two different levels of 5 and 10% by weight. For the plain cement concrete mixes and that with SF, a superplasticizer (naphthalene based) was added (0.6 to 0.9% by weight of cement) at the time of mixing to make the mix workable. Table 1 describes the mix proportions used in the present study, while Table 2 presents the oxide composition of OPC (ASTM Type I) and SF used in the present study. The average fineness modulus for fine aggregate (silica sand) was 3.1 and that for coarse aggregate (maximum size 20 mm, crushed granite) was 6.5. The specific gravity for both the fine and coarse aggregates was 2.60.

Test specimens of three different sizes were prepared by using each mix proportion as shown in Table 1 to suit the requirements of different tests conducted as part of the experimental work. Test specimens of dimensions 100 × 100 × 400 mm, diameter 95 mm, thickness 55 mm, and 100 × 100 × 100 mm were prepared for the soaking test, RCPT and electrical resistivity tests respectively. Test specimens prepared with each mix proportion after demoulding (24 h after casting) were divided into three batches (A, B and C). Test specimens under batch A were subjected to moist curing by immersing in water for 2 days, while those under B and C were subjected to similar curing for 6 and 27 days respectively.

Table 1
Different types of mix proportions used in the present study

Specimen type	w/b ratio	Cement (kg m^{-3})	Silica fume (kg m^{-3})	Fine aggregate (kg m^{-3})	Coarse aggregate (kg m^{-3})	Water content (kg m^{-3})
100% OPC concrete	0.40	450	0.00	735	993	180
	0.50	370	0.00	846	934	185
	0.60	317	0.00	914	895	190
100% OPC mortar	0.40	852	0.00	1011	Nil	341
	0.50	748	0.00	1011	Nil	374
	0.60	666	0.00	1011	Nil	400
5% SF concrete	0.50	352	18	842	929	185
10% SF concrete	0.50	333	37	837	924	185
5% SF mortar	0.50	702	37	1011	Nil	370
10% SF mortar	0.50	658	73	1011	Nil	366

2.3. *Test details*

2.3.1. *Soaking test*

Soon after the completion of pre-curing (3, 7 and 28 days) all the test specimens (100 × 100 × 400 mm) were immersed in sodium chloride (NaCl) solution (19,380 ppm Cl^- conc.). During the period of immersion in salt solution, the test specimens were withdrawn periodically from the soaking tank (7, 14, 28, 56 and 90 days) to measure the depth of chloride penetration. For this purpose, the prisms were first split on a compression-testing machine and the freshly split surfaces were then sprayed with 0.10 N silver nitrate ($AgNO_3$) solution. The $AgNO_3$ solution preferentially reacts with the free-chlorides present in the hardened matrix to form a white precipitate of silver chloride (AgCl), and at greater depths, where free-chlorides are absent, $AgNO_3$ reacts with the hydroxides to form a brown precipitate of silver oxide (AgO). Thus, the depth of chloride penetration is clearly indicated as the boundary of colour change. The depth measurements were made from all the four faces at intervals of 20 mm and the measurements made close to the corners and ahead of the coarse aggregates were ignored.

2.3.2. *Rapid chloride permeability test (RCPT)*

After the pre-curing (3, 7 and 28 days) the thickness of all the mortar and concrete cylindrical test specimens (95 mm diameter × 55 mm thickness) were reduced to 51 ± 1 mm by grinding on both the ends. The specimens were then evacuated by following the procedure as described in AASHTO T 277-89 [4].

The test procedure followed in the present study was in conformity with the AASHTO specification T277-89 [4] and ASTM C 1202-94 [10]. The positive reservoir of the cell was filled with 0.30 N sodium hydroxide (NaOH) solution, while the negative reservoir was filled with 3.0% NaCl solution. A direct current (DC) of 60 ± 0.10 V was applied across the specimen and the resulting current was recorded at 5-min interval covering a total period of 6 h. By knowing the current and time history, the total charge passed through the specimen was computed by Simpson integration. During the RCPT, temperatures of the specimens were monitored (the Joule effect) manually during the test period and were observed to be close to room temperature.

2.3.3. *Electrical resistivity*

Soon after pre-curing (3, 7 and 28 days), the resistivities of all the cubes (100 × 100 × 100 mm) were measured using a resistivity meter (Model RM MKII) operating on Wenner's principle (Four Probe Technique). Four sets of measurements were taken on each of the four side faces of the cube and they were then averaged to obtain a mean value. No measurements were done on the cast and the bottom faces of the cubes to avoid discrepancies arising due to the effects of excessive bleeding and compaction respectively. All the cubes were saturated in water prior to

Table 2
Oxide content of OPC and SF used in the present study

Type of binder	SiO_2 (%)	Al_2O_3 (%)	Fe_2O_3 (%)	CaO (%)	MgO (%)	SO_3 (%)	K_2O (%)	Na_2O (%)
OPC	21.1	5.24	3.10	64.39	1.10	2.52	0.57	0.23
SF	93.0	0.20	0.05	—	0.51	0.05	0.20	0.22

the resistivity measurement. The contact surfaces of the probes were maintained in a moist state to ensure good electrical contact with the measuring surface.

3. Results and discussion

In the following section, the results for the test specimens prepared with concrete and mortar mixes with and without SF are presented and discussed.

3.1. Depth of chloride penetration

3.1.1. Depth of chloride penetration through the plain cement concrete and mortar specimens

Figure 1 depicts the relationship between the depth of chloride penetration (mm), the square root of immersion period (days) in salt solution (19,380 ppm chloride conc.), and the pre-curing period for both mortar and concrete specimens (100 × 100 × 400 mm). The data presented in Fig. 1 pertain to the plain cement mortar and concrete specimens prepared by using a mix having a w/b ratio of 0.50.

It is evident from Fig. 1 that the depth of chloride penetration, as is widely known, depends on the period of immersion in the salt solution and the pre-curing period. However, for both mortar and concrete, the pre-curing period (3, 7 and 28 days) has a marginal effect on the resistance to chloride penetration compared to the period of immersion in salt solution. Furthermore, for all the pre-curing and immersion periods, the depths of chloride penetration through the concrete are greater compared to those through the mortar. This implies a higher rate of chloride penetration through the concrete (or its lower resistance against chloride penetration) than through the mortar of similar w/b ratio and pre-curing period but of different aggregate and cement contents. Initially, the differences in the depths of chloride penetration between concrete and mortar specimens are small (7 days) for all the pre-curing periods; however, with increasing period of immersion in salt solution the difference grows gradually and becomes significant around 90 days. The mortar because of higher cement content and, therefore, because of the higher tricalcium aluminate (C_3A) content, will have a greater ability to bind chlorides in the form of Friedel's salt compared to the concrete mix. The visible difference between mortar and concrete which begins to appear around 7 days is perhaps the commencement of the effect of significant chloride binding in the mortar. Relatively higher chloride binding in the mortar leads to the deposition of the voluminous chloride bearing phase such as Friedel's salt in the coarser pores ($> \sim 60$ nm diameter) causing greater pore constriction and tortuosity (connectivity) [11}. Thus, the implications of higher chloride binding in mortar are a greater degree of pore constriction and the generation of a tortuous pore structure, which impede the subsequent chloride penetration through the mortar. The above appears to be the cause of the superior performance of the mortar in the soaking test compared to the concrete. The higher rate of chloride penetration through the concrete may be partly due to the presence of aggregate–paste transition zones; however, its influence is believed to be negligible in well-cured concrete (7 and 28 days) specimens [9].

The plain cement mortar and concrete specimens prepared with mixes of 0.40 and 0.60 w/b ratios also showed trends similar to that described in Fig. 1. The above trend was also true for the mixes containing SF. The depths of chloride penetration measured for both plain cement mortar and concrete specimens during the 90-day soaking test were then used to compute the chloride penetration coefficient K (mm per week).

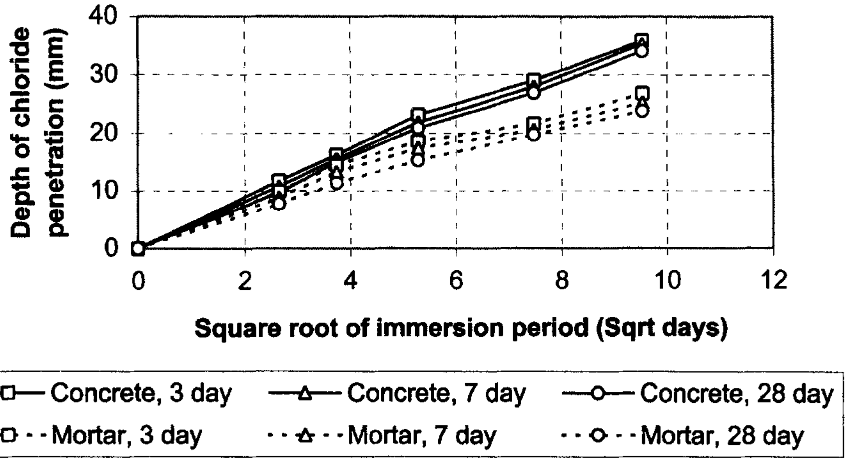

Fig. 1. Relationship between the depth of chloride penetration and square root of immersion period for plain cement concrete and mortar specimens pre-cured for different periods.

The magnitudes of K were estimated by using the empirical relationship eqn (1) between the depth of chloride penetration (X) and duration of immersion in salt solution (t) as proposed by Bakker [12].

$$X = a + K\sqrt{t} \tag{1}$$

In the present study X was varying linearly with $\sqrt{t}$ and for all the mixes used in the present investigation the linear trend showed correlation coefficients (R) close to unity. Table 3 presents the estimated values of a for all the mix proportions used in the present investigation. Table 3 demonstrates the lack of a well-defined relationship between a and the mix design parameters. For example, for the plain cement mortar having a w/b ratio of 0.40, the magnitudes of a irrespective of the pre-curing periods are lower compared to the values of a for the concrete of similar w/b ratio but of relatively higher aggregate content. On the contrary, for the plain cement mortar mixes having w/b ratio of 0.50, the magnitudes of a are consistently higher irrespective of the pre-curing periods compared to the values of a for the concrete of similar w/b ratio and having higher aggregate content. For the w/b ratio of 0.60, the magnitudes of a are higher for the mortar for only few pre-curing periods (7 and 28 days) compared to the corresponding ones for the concrete of similar w/b ratio but of relatively higher aggregate content. Furthermore, for all the mixes the magnitude of a was found to decrease consistently with increasing pre-curing periods, although this was not true for the plain cement concrete mix having a w/b ratio of 0.40. A similar trend was observed for the concrete and mortar mixes containing SF. Therefore, the magnitude of a is believed to be more or less an artefact of the curve-fitting process. However, it should be noted that the estimated values of a are small compared to the estimated values of K; therefore, K alone is used in the present study as a parameter for comparing the resistance against chloride penetration.

Figure 2(a) demonstrates the relationship between K and the parameters such as the w/b ratio of the mix and the pre-curing period. As generally expected, for the plain cement mortar and concrete specimens pre-cured for a similar duration, an increase in w/b ratio leads to larger K or faster rate of chloride penetration. Furthermore, as normally expected, for plain cement concrete and mortar specimens of all w/b ratios, K marginally decreases (decreasing X) with increasing pre-curing duration. For a given pre-curing duration and w/b ratio of the mix, the magnitudes of K for the plain cement concrete specimens are also significantly higher compared to the corresponding K for the plain cement mortar specimens. In other words, the resistance of plain cement concrete of relatively higher aggregate content against chloride ingress is lower than the plain cement mortar of similar w/b ratio and pre-curing period. From Fig. 2(a) it is also apparent that an increase in w/b ratio leads to a greater change in the magnitude of K for the plain cement concrete compared to that for the plain cement mortar.

3.1.2. *Depth of chloride penetration for the concrete and mortar specimens containing SF*

The depths of chloride penetration through concrete and mortar specimens (0.50 w/b ratios) containing SF also increased with time. Similar to the plain cement concrete specimen, the depth of chloride penetration through the concrete specimen containing SF after 90 days immersion in salt solution was higher compared to that through the mortar specimen containing SF. The depths of chloride penetration measured for both concrete and mortar specimens containing SF for 90 days immersion in salt solution were then used to estimate K values as explained earlier.

Table 3
Estimated values of a for different mixes used in the investigation

w/b ratio	Pre-curing period	Estimated value of a					
		Concrete	Mortar	Concrete with 5% SF	Concrete with 10% SF	Mortar with 5% SF	Mortar with 10% SF
0.40	3	1.928	1.224	—	—	—	—
	7	1.387	0.634	—	—	—	—
	28	1.452	0.465	—	—	—	—
0.50	3	1.506	2.490	1.901	2.160	1.888	1.819
	7	1.004	2.056	1.465	1.381	1.340	1.344
	28	0.728	1.194	0.500	0.645	0.527	0.679
0/60	3	1.052	0.953	—	—	—	—
	7	0.794	0.815	—	—	—	—
	28	0.565	0.652	—	—	—	—

Figure 2(b) shows the relationship between *K* and the pre-curing period for the mortar and concrete specimens containing SF. From this Figure it is evident that for a given SF addition to the concrete and mortar mix, the resistance against chloride penetration increases (lower *K* or lower *X*) with increasing pre-curing period. For both concrete and mortar mixes, increasing SF content in the mix also increased significantly their resistance against chloride penetration (lower *K*), which is explained by greater degree of pore refinement and filler action due to SF. The magnitudes of *K* were large for the concrete mix containing 5% SF compared to the mortar of similar w/b ratio and pre-curing period but of relatively lower aggregate content. For the 10% SF addition, the *K* values for concrete were slightly larger than those for the mortar of similar w/b ratio and pre-curing period but of lower aggregate content. The above results suggest the lower resistance of concrete containing SF against chloride penetration.

3.2. Total charge passed from RCPT

3.2.1. Total charge passed through plain cement concrete and mortar specimens

Figure 3(a) demonstrates the relationship between the total charge passed (coulombs), the pre-curing duration (days) and the w/b ratios (0.40, 0.50 and 0.60) for plain cement concrete and mortar specimens. From this figure it is evident that for a given pre-curing period, an increase in w/b ratio leads to greater amount of charge passed through the plain cement concrete and mortar specimens. In other words, the resistance of plain cement concrete and mortar specimens against chloride penetration decreases with increasing w/b ratio of the mix as a result of the porous microstructure. It is also true that for a given w/b ratio of the mix, the longer the pre-curing duration the lower is the charge passed through the plain cement concrete and mortar specimens (or the higher is the resistance of plain cement mortar and concrete against

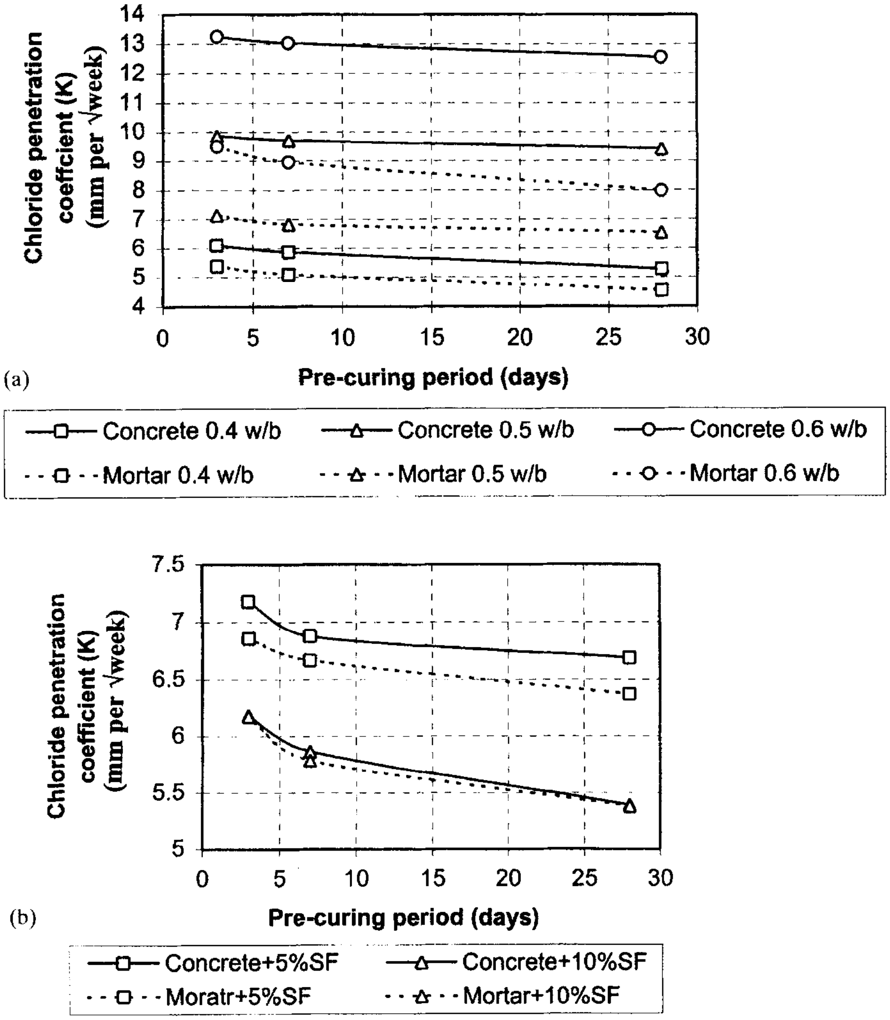

Fig. 2. Relationship between the chloride penetration coefficient and pre-curing duration for: (a) plain cement concrete and mortar specimens of different w/b ratios; (b) concrete and mortar specimens containing SF (0.5 w/b ratio).

chloride penetration) due to the denser microstructure. The above observations are in good agreement with the soaking test results (Figs 1 and 2(a)).

For a given pre-curing duration and w/b ratio, the total charge passed through the mortar specimen is significantly higher compared to that through the plain cement concrete specimen of relatively higher aggregate content. Generally, the charge passed through the mortar is higher by at least a factor of ~2 than that through the concrete. Since the higher the charge passed the lower is the resistance against chloride penetration [4,5], this implies that the resistance of the mortar (lower aggregate content) against chloride penetration is lower than the concrete (higher aggregate content) of similar w/b ratio and pre-curing period. The above contradicts the observation made from the soaking test, which based on the 90-day immersion test demonstrated the mortar (lower aggregate content) to be relatively more resistant than the concrete (higher aggregate content) of similar w/b ratio and pre-curing period.

3.2.2. Total charge passed through concrete and mortar specimens containing SF

Figure 3(b) shows the relationship between the total charge passed and the pre-curing period for the mortar and concrete specimens containing SF (5% and 10%). For a given SF content in the concrete and mortar mix, the charge passed decreases with increasing pre-curing period. For a given pre-curing period, the total charge passed also decreased with increasing the SF content in the concrete and mortar mix as a result of higher pore refinement and filler action due to SF. However, for both 5 and 10% SF additions to the mix, the charge passed through the mortar (lower aggregate content) was significantly higher compared to the concrete

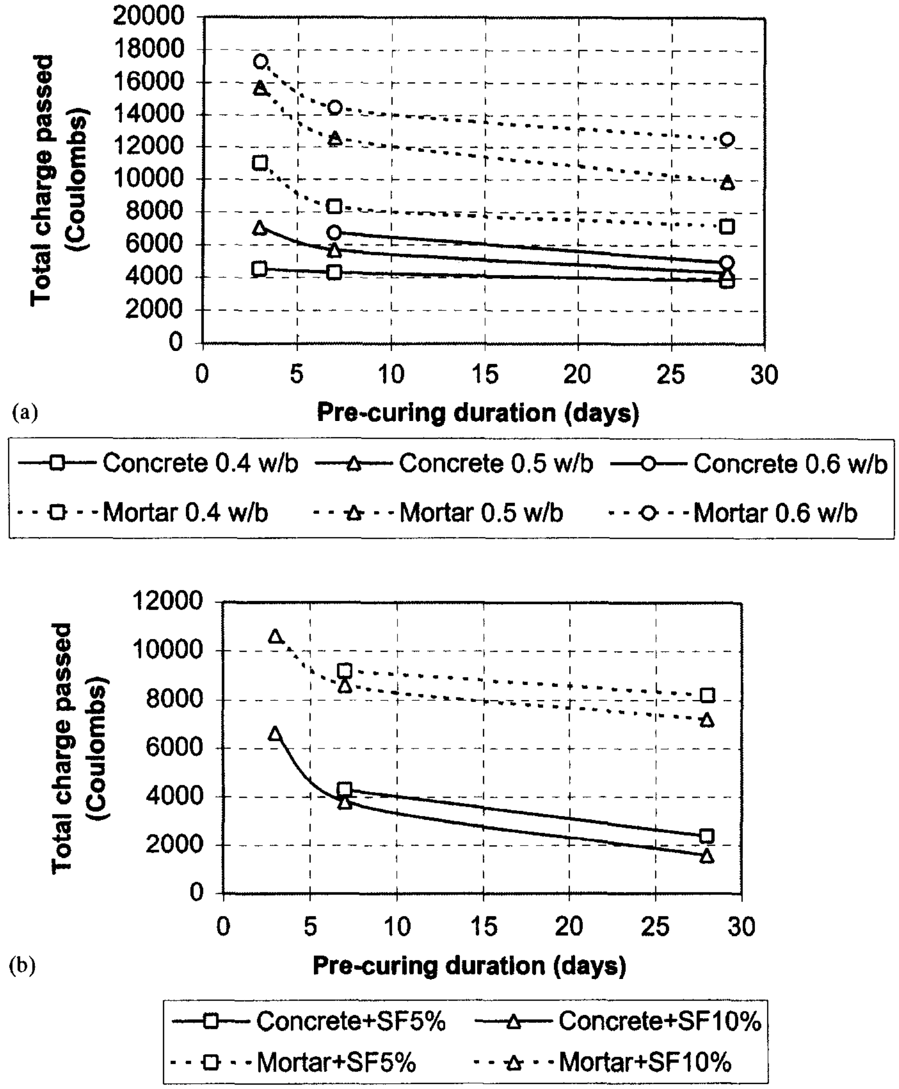

Fig. 3. Relationship between the total charge passed and pre-curing duration for: (a) plain cement concrete and mortar specimens of different w/b ratios; (b) concrete and mortar specimens containing SF (0.5 w/b ratio).

(higher aggregate content) of similar w/b ratio and pre-curing period. This implies the greater resistance of concrete specimens (higher aggregate content) containing SF (5 and 10%) against chloride penetration compared to the mortar specimen (lower aggregate content) containing SF. The above contradicts the 90-day soaking test result, which suggested the mortar specimens containing SF (lower aggregate content) to be more resistant against chloride penetration than the concrete (higher aggregate content) specimens containing SF.

Thus, for the plain cement concrete and mortar specimens, the RCPT and 90-day soaking test results are contradictory when it comes to compare their resistance against chloride penetration. This contradicts the findings reported in AASHTO T277-89, which demonstrated good correlation between the RCPT results and 90-day chloride ponding test results carried out on companion slabs cast with the same concrete mix [4]. The above observation is also true for the concrete and mortar specimens containing SF.

Many researchers have previously employed the soaking test to assess the depth of chloride penetration through hardened cement matrix and have recommended it to be a reliable and fairly accurate technique [13,14]. AASHTO 259 [15] also recommends the soaking test for evaluating the depth of chloride penetration through hardened cement matrix. Hence, the accuracy and reliability of the results obtained through the soaking test cannot be doubted. This leads us to question the validity of the RCPT as a reliable test method to evaluate the chloride permeability of concrete. In terms of material composition, the main difference between the plain cement mortar and concrete mix is the presence of a greater volume fraction of aggregates or lower cement fraction in the latter, which was maintained deliberately as explained earlier. The above is also true for the concrete and mortar mixes blended with SF. Furthermore, considering the duration of the test (6 h), binding of chlorides by cement phases during the RCPT is believed to be of negligible magnitude in both concrete and mortar specimens. The lower charge passed through the concrete specimens also indirectly indicates the insignificant influence of aggregate–cement paste transition zones on the RCPT results.

The mechanism of electrical conduction through the hardened cement matrix is essentially electrolytic in nature and the principal ions that are responsible for the ionic conduction are Na^+, K^+, Ca^{2+}, and OH^- ions present in the pore water [8]. During the RCPT, the electrical conduction through the specimen is also electrolytic in nature and the majority of electrical conduction as one understands from the principle of RCPT should be due to the chloride ions present in the negative reservoir of the cell. It is quite logical to expect part of the electrical conduction during the RCPT to take place via the ions present in the pore solution (Na^+, K^+, Ca^{2+}, and OH^-) of the specimen, apart from the chloride ions present in the negative reservoir. However, the current carried by the cations such as Na^+ and K^+ present in the pore solution of the specimen can be considered to be insignificant due to their lower ionic conductivity, as these ions migrate in a solvated state (surrounded by water molecules) under the influence of an electric field [16]. Similarly, the contribution of Ca^{2+} ions present in the pore solution should also be negligible due to their presence in the pore solution in very low concentration [17]. The large ionic radii of Ca^{2+} also hinder the mobility of Ca^{2+} ion during RCPT. However, the role of OH^- ions present in the pore solution of the specimen during RCPT is a matter of controversy. Andrade [6] reported that the OH^- ions present in the pore water of the specimen act as a "supporting electrolyte" and carry a significant proportion of the total current during the RCPT owing to their higher ionic conductivity ($198.5\,\Omega\,cm^{-2}\,eq^{-1}$) compared to the chloride ion ($76.34\,\Omega\,cm^{-2}\,eq^{-1}$). On the contrary, Cabrera and Claisse [18] based on their RCPT results have concluded that only in the case of a hardened cement matrix containing SF do the OH^- ions present in the pore solution of the specimen contribute to the total charge passed, while the charge passed through the hardened plain cement matrix is entirely due to the chloride ions. However, no information is available in the published literature on the quantity or the proportion of current transported exclusively by the OH^- ions during the RCPT. The proportion of current transported by OH^- ions also depends on the number of OH^- ions present in the pore water, which is controlled by factors such as the cement content of the mix, the alkali content of the cement and the type and percentage of mineral admixtures present in the mix [17,19].

The results reported by McCarter et al. [3] on chloride absorption studies indirectly suggest the insignificant role of OH^- ions during the RCPT. The resistivity of the pore water present in OPC and OPC blended with different mineral admixtures at various stages of hydration tend to lie well within a narrow range of $50–100\,\Omega\,cm$ [20–23], while for 1 M and 0.50 M solutions of NaCl the resistivities are substantially lower at about 18 and $30\,\Omega\,cm$ respectively [3]. In the RCPT, the concentration of NaCl solution used in the negative reservoir equals 0.50 M, which is considered to be reasonably high. As the negative reservoir of the RCPT cell is filled with NaCl solution of higher concentration (0.50 M), there is a greater possibility for the concentration of NaCl within the specimen to build up during the test to a value as high as about 1 M, due to the migration of Na^+ from the positive reservoir and Cl^- from the negative reservoir of the cell. As a result of such electrical migration during the RCPT, the conductivity of the resulting pore solution present within the specimen may be close to that corresponding to 1 M solution of NaCl [3]. The major implication of such a high build-up of NaCl concentration within the specimen during the RCPT is the inundation by the Cl^-, and the possible conduction during the RCPT by other ions, especially the OH^- present in the pore solution of the specimen. This leads us to believe that the OH^- present in the pore solution of the specimen has a negligible role during the RCPT. The above is also supported by the fact that no information is available in the published literature on the quantity or the proportion of the charge transported by the OH^- during the RCPT.

Since in the present investigation the volume fraction of the aggregate (or the cement fraction) is used as the main variable in the mix; apart from the w/b ratio and pre-curing period, it is important to understand the role of aggregates on RCPT results vis-à-vis on the electrical conduction during the RCPT.

3.3. Electrical resistivity

3.3.1. Electrical resistivities of plain cement concrete and mortar specimens

Figure 4(a) shows the relationship between the electrical resistivity (KΩ cm), the pre-curing duration (days) and the w/b ratios of the mix for plain cement mortar and concrete specimens. As expected, for a given pre-curing duration decreasing the w/b ratio of the mix increased the electrical resistivity, and for a given w/b ratio, the longer the pre-curing duration the higher is the electrical resistivity for both concrete and

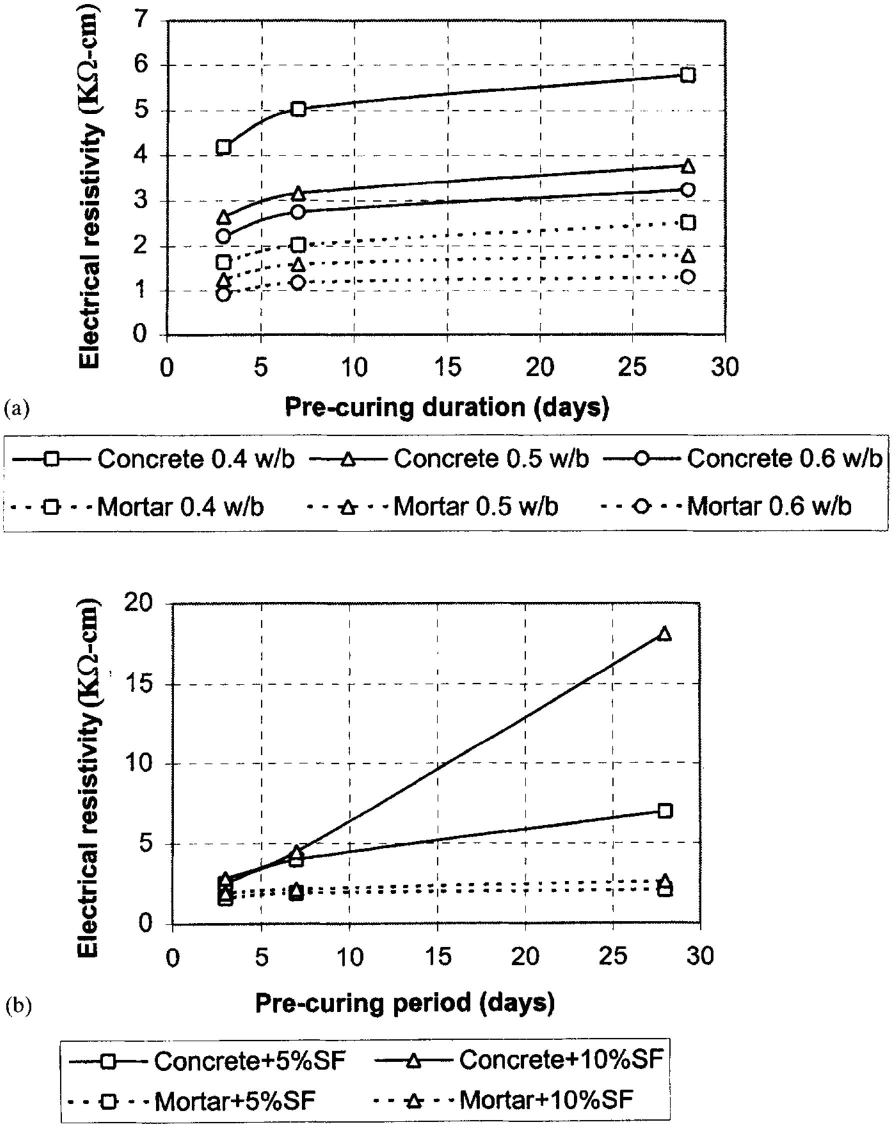

Fig. 4. Relationship between the electrical resistivity and pre-curing period for: (a) plain cement concrete and mortar specimens of different w/b ratios; (b) concrete and mortar specimens containing SF (0.5 w/b ratio).

mortar specimens. The reasons for the above are explained below.

In the present study as mentioned before, crushed granite was used as the coarse aggregate in the concrete mix while, the silica sand was used as the fine aggregate in both concrete and mortar mixes. Electrical resistivities of silica sand and granite are extremely large compared to that of the neat cement paste. For example, the electrical resistivity of neat cement paste lies in the region of 25–45 Ω m, whilst those for granite and silica sand are in the region of 5×10^3–1×10^6 and 3.8×10^4–1.2×10^{12} Ω m respectively [8]. The relatively higher electrical resistivities of the aggregates lead to the conduction of the majority of the ionic current during the RCPT through the capillaries formed in the cement paste, which provide the paths of least resistance for electrolytic conduction. Furthermore, for a given concrete or mortar of a fixed aggregate content, the electrical resistivity can still be varied by varying the w/b ratio and the pre-curing periods. An increase in w/b ratio or decrease in pre-curing period for both concrete and mortar leads to an increase in the proportion of unsegmented or continuous capillaries in the cement paste [24], and thus favours the ionic conduction (or decreases the electrical resistivity).

From Fig. 4(a) it is also evident that for the same w/b ratio and pre-curing duration, the electrical resistivities for plain cement concrete (higher aggregate content) are significantly higher compared to those for mortar (lower aggregate content). For example, for plain cement concrete specimens having w/b ratios of 0.40, 0.50 and 0.60 after 28 days of pre-curing the electrical resistivities were between 3000 and 6000 Ω cm. On the other hand, for the plain cement mortar of above w/b ratios (0.40, 0.50 and 0.60) and pre-curing duration (28 days) the resistivities are well below 3000 Ω cm. Thus, the higher resistivities measured for the plain cement concrete specimens correlate well with the lower charge passed through the concrete as indicated through the RCPT.

3.3.2. Electrical resistivities for the concrete and mortar specimens containing SF

Figure 4(b) presents the relationship between the electrical resistivity and the pre-curing period for the concrete and mortar specimens containing SF. For a given SF content in the mix, the electrical resistivities for both concrete and mortar increased with the pre-curing period; however, the rate of increase for the former was significant from 7 days onwards. For a given pre-curing period the electrical resistivities also increased with the proportion of SF in the concrete and mortar mix due to the denser pore structure. However, the increase in the magnitude of the electrical resistivity with increasing SF content was marginal for the mortar specimen containing SF. Similar to the plain cement concrete, the electrical resistivities of the concrete (higher aggregate content) blended with SF (5 and 10%) were higher compared to the mortar (lower aggregate content) of similar w/b ratio and pre-curing period.

As pointed out earlier the resistivities of the aggregate (fine or coarse) are higher by several orders of magnitude compared to the neat cement paste. As a result of this, the majority of the ionic current during the RCPT will be conducted through the capillaries formed in the cement paste, and these capillaries provide paths of least resistance for ionic conduction. For a mix of fixed cement content, the capillary pore volume is controlled by the degree of hydration and the w/b ratio of the mix. Thus, the higher the paste content in the mix the lower is the electrical resistivity of the hardened cement matrix. For a given w/b ratio and pre-curing period, the resistivities of plain cement concrete and the concrete with SF are relatively higher (than mortar with and without SF) due to the presence of a lower paste content in the mix. On the other hand, the resistivity of the hardened plain cement mortar and the mortar with SF are lower (than concrete with and without SF) due to the higher paste content in the mix.

The above discussion clearly indicates the strong dependence of electrical resistivity or, indirectly, the dependence of RCPT results on the volume fraction of cement/aggregates in the mix or the microstructure present in the hardened matrix. The tortuous microstructure may also impede the conduction of electrical current through the hardened cement matrix and thereby increase the electrical resistivity. The electrical resistivity apart from depending on the microstructure is also known to depend on the conductivity of the pore solution present in the specimen [21]. Thus, the lower electrical resistivity of the plain cement mortar and that with SF may be partly due to the higher ionic content in the pore solution as a result of the greater cement content in the mix. However, as explained earlier, during the RCPT, Cl^- swamps out the possible conduction by other ions present in the pore solution of the specimen.

In order to understand the interdependence between the three properties of the concrete measured in the present investigation (K, charge passed from RCPT and electrical resistivity), the charge passed is first graphically correlated with K and then with electrical resistivity. Figure 5 depicts the relationship between the total charge passed and K for all the different mixes used in the present investigation. In this figure, for convenience the number of mixes has been reduced to four types of mixes (plain cement mortar, plain cement concrete, concrete+SF (5 and 10%) and mortar+SF (5 and 10%)). For the plain cement mortar mix the charge passed is linearly ($R = 0.878$) related to K. However, for the plain cement concrete specimen

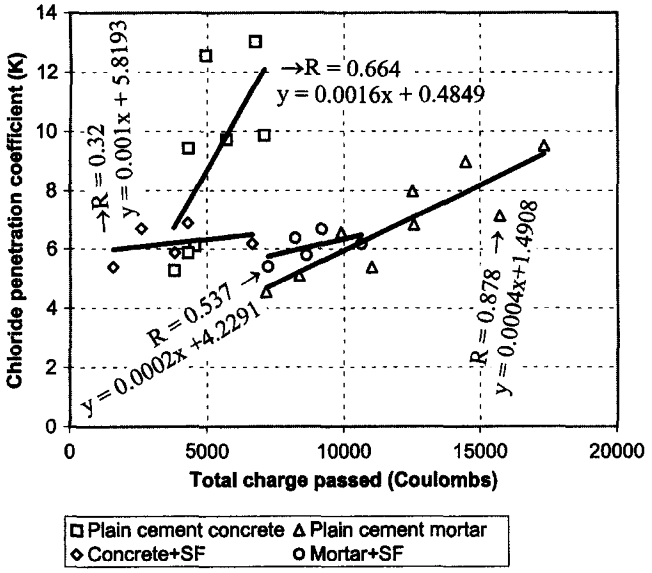

Fig. 5. Relationship between the total charge passed and chloride penetration coefficient (*K*) for different concrete and mortar mixes.

the trend showed a lower *R* of 0.664 for linearity. The higher aggregate content in the plain cement concrete mix is believed to be the cause of the poor linear relationship between *K* and total charge passed as the latter is controlled by the electrical resistivity as already shown. The addition of SF to the concrete and mortar mix resulted in a poor linear relationship between the total charge passed and *K*. The values of *R* for a linear trend were as low as 0.32 and 0.537 for concrete and mortar containing SF respectively. Thus, except for the plain cement mortar mix, all other mixes failed to show a good linear relationship between *K* and the total charge passed. Figure 6 shows the relationship between the total charge passed and the electrical resistivity for the above mixes. For all the above four mixes, the total charge passed decreased exponentially with increasing electrical resistivities. From this figure it is also evident that all the four types of mixes follow an exponential trend with a fairly good correlation coefficient (refer to Fig. 6 for *R* and equation). Thus, regardless of the aggregate and SF content in the mix, the total charge passed decreases exponentially with increasing electrical resistivity. On the other hand, with the exception of plain cement mortar, for all the other three types of mixes the linear relationship between the total charge passed and *K* was poor. This suggests that for those mixes containing a higher volume fraction of aggregates, and also for those mixes blended with SF, the linear relationship between the total charge passed and *K* will be poor.

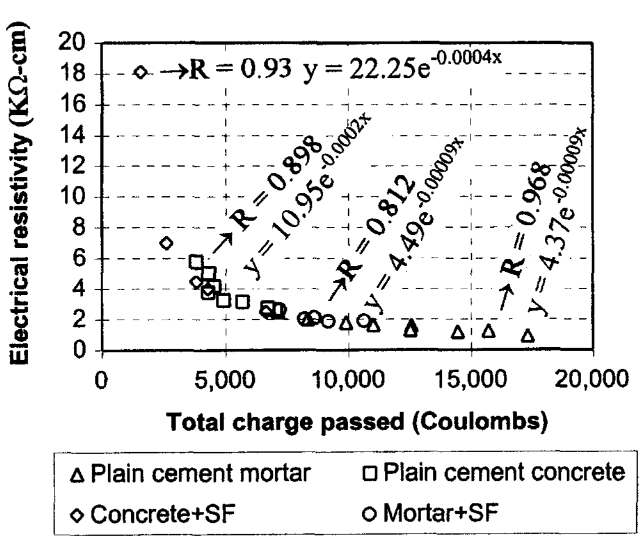

Fig. 6. Relationship between the total charge passed and electrical resistivity for different concrete and mortar mixes.

Even though the present investigation is carried out using more controlled mixes, unlike the mixes used in field structures, the results cannot be ignored, as the study provides a clear picture of the mechanism involved. The present study emphasizes the need for greater caution, especially when interpreting and also when comparing the RCPT results for mixes differing in aggregate content, to avoid misleading conclusions. The above applies to both 100% OPC mixes and those mixes blended with SF. Nevertheless, the RCPT can still be used with caution as an important tool in quality control and inspection of structural concrete.

4. Conclusions

The conclusions derived from the present experimental investigation are presented below.

1. For the plain cement concrete and mortar specimens, regardless of the w/b ratios (0.40, 0.50 and 0.60) and pre-curing duration (3, 7 and 28 days), the depths of chloride penetration increased with increasing period of immersion in salt solution (up to 90 days). For a given immersion period, the depths of chloride penetration through concrete and mortar decreased insignificantly with increasing pre-curing period, but as generally expected, the depths of chloride penetration increased significantly with increasing w/b ratios.
2. The 90-day soaking test results demonstrated the plain cement mortar specimens (0.4, 0.5 and 0.6 w/b ratio) of lower aggregate content (higher cement content) to be more resistant against chloride penetration compared to the plain cement concrete specimen of similar w/b ratios but with higher aggregate content (lower cement content). The above trends remained unchanged even after the addition

(5 and 10%) of silica fume (SF) to the concrete and mortar mixes.

3. Contrary to the soaking test, the RCPT demonstrated the plain cement mortar specimens (0.4, 0.5 and 0.6 w/b ratios) of lower aggregate content (higher cement content) to be less resistant against chloride penetration than the corresponding plain cement concrete specimens of similar w/b ratio but with higher aggregate content (lower cement content), which was evident by the passage of a relatively higher total charge through the former. The above trend remained unchanged despite the addition of SF to the concrete and mortar mixes.
4. The measured electrical resistivities for the mortar specimens with and without SF (lower aggregate and higher cement content) were significantly lower than those for the concrete specimens (higher aggregate and lower cement content) with and without SF, which explain the reason for the passage of higher charge through the former during the RCPT.
5. The lower aggregate fraction (higher cement fraction) in the plain cement mortar and the mortar blended with SF is shown to mislead the RCPT results. A higher cement fraction in the mortar mix with and without SF promotes the passage of greater charge as the resistivity of the cement paste is lower by several orders of magnitude compared to that of the aggregates (fine and coarse).
6. Regardless of the aggregate and SF content in the mix, the total charge passed through the concrete and mortar mix decreased exponentially with increasing electrical resistivity. On the other hand, the linear relationship between total charge passed through the concrete and mortar mix and the chloride penetration coefficient (*K*) was poor when the aggregate content in the mix was high (plain cement concrete), and also when the concrete or mortar mix was blended with SF. However, for the mix with a relatively lower aggregate content and with no SF blending (plain cement mortar) a fairly good linear relationship was shown between total charge passed and *K*.
7. Although the mixes used in the present investigation are more controlled mixes than in previous studies, the results derived from the present study are useful in understanding the mechanism involved. The results emphasize the need for greater caution in interpreting and especially in comparing the RCPT results for mixes with varying aggregate contents. The volume fraction of aggregate in the mix has to be taken into account when interpreting the data on total charge to avoid misleading interpretations. The present study also suggests the need to consider the volume fraction of aggregates present in mixes blended with SF when interpreting the RCPT results.

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