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Modified electrical conductivity test method for evaluation concrete permeability

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Abstract. Standard test method for bulk electrical conductivity (ASTM C1760) provides a rapid indication of the concrete's resistance to the penetration of chloride ions by diffusion. In this paper a new approach for assessing the bulk electrical conductivity of saturated specimens of hardened concrete is presented. The test involves saturating concrete specimens with a 5 M NaCl solution before measuring the conductivity of the samples. By saturating specimens with a highly conductive solution, they showed virtually the same pore solution conductivity. Different concrete samples yield different conductivity primarily due to differences in their pore structure. The feasibility of the method has been demonstrated by testing different concrete mixtures consisting ordinary and blended cement of silica fume (SF) and calcined perlite powder (CPP). Two standard test methods of RCPT (ASTM C1202) and Bulk Conductivity (ASTM C1760) were also applied to all of the samples. The results show that for concretes containing SF and CPP, the proposed method is less sensitive towards the variations in the pore solution conductivity in comparison with RCPT and Bulk Conductivity tests. It seems that this method is suitable for the assessment of the performance and durability of different concretes containing supplementary cementitious materials.

Keywords: concrete; chloride permeability; conductivity; pore solution

1. Introduction

It is widely known that deterioration of concrete due to corrosion of reinforcement is one of the most significant durability problems that the construction industry is concerned with (Safehian and Ramezanianpour 2013). The corrosion of steel in concrete normally occurs as a result of either the reduction in alkalinity at the steel, due to carbonation of concrete or leaching of alkalis, or the presence of a significant quantity of chloride ions in the concrete (Safehian and Ramezanianpour 2015). Considering the importance of chloride ion penetration mechanism, different types of tests have been employed up until now to measure the resistance of different types of concrete against

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chloride ingress (Hooton and Karkar 2012).

The early methods of measuring the diffusion coefficient of chloride ions into the concrete were based on immersion of concrete samples in a saline solution. Later, in these methods, and after the conditions of exposing, the chloride ion diffusion coefficient was obtained by using the determination profile of the influence of chloride ions, and fitting of Fick's second law (Bagheri and Zanganeh 2012). But one of the weaknesses of these methods was the long time that was required for the tests, under the normal conditions.

Regarding to that, the chloride diffusion coefficient was one of the important factors in determining the durability of the concrete, there was paid a great attention to the use of accelerated methods (Wang 2015). One of these approaches was the increases of the concentration of dissolved chloride ions that were used (ASTM 2011, ASTM 2010). But in this case, the diffusion behavior might not follow Fick's law, due to the interference and interaction of the ions (Poulsen and Mejlbro 2010).

Another approach was to use an electric potential as the external force to increase the penetration of ions. This approach was widely used (Spragg *et al*. 2013). By applying an external electric potential the transportation of ions was done towards an electric field.

One practical use of electrical measurements is the standard test that is commonly referred to as the rapid chloride permeability test (RCPT) (ASTM 2012a). in the early 1980's, Whiting (Whittington *et al*. 1981) proposed the first electrically accelerated test, called the coulomb test owing to the measurement of total charge that passes through the saturated specimen within a 6-hour interval when a constant voltage (60 volts) is applied. The total charge passed through the sample is then used as a merit of chloride permeability. While widely used, the RCPT has a few shortcomings due to the relatively long sample preparation time, its destructive nature, and sample heating, which influences the results (Julio-Betancourt and Hooton 2004, Snyder *et al*. 2000 Rupnow and Icenogle 2011).

In Norway, a similar method was developed based on observation of migration rate of chloride ions in concrete and it was well known as "chloride permeability" (Nordtest 1995). Anyway, the results of the experimental method were qualitative parameters that depended on experimental conditions. It could be said, the observed penetration rate of chloride ions depended on the concentration of salt solution and the applied voltage (Tang *et al*. 2011).

Conventional diffusion methods have shown that the presence of other types of ions within the system additionally have an effect on the rate of chloride intrusion (Sun *et al*. 2011). Thus, the rate of chloride penetration might increase significantly due to a change in type of cation from sodium to calcium in the chloride solution.

On the other hand, in all the methods above, the electric potential does not play a significant role in speeding up the diffusion process. Namely, the increase in the flux of ions is predominantly due to conduction mechanisms, rendering these methods conduction experiments in their actuality, with negligible effects from diffusion (Streicher and Alexander 1995).

In the other method proposed by Dhir *et al.* (1990), the chloride current in the steady state under the potential difference of 10 volts is measured, which is used to extract the chloride diffusion coefficient of concrete (D) empirically.

In the early 1990s in Sweden, Nilsson and Tang (1993) were the first ones to provide accelerated method in which the relationship between the diffusion and migration theory was used to calculate the diffusion coefficient of chloride ions. In this method, the diffusion coefficient was calculated after applying an electric potential, based on the observation of the depth of the chloride ions penetration. The advantages could be pointed were its ease, relatively short time, and background theory.

The calculation of the chloride diffusion coefficient in this method is based on the assumption of constant electric field. Also, it does not take into account the interactions between different ionic species and the electrostatic coupling of ions in the multi-component pore electrolyte solution (Xia and Li 2013). However, In recent years, the method has been further developed and widely used (Tang 2005).

On the other hand, the electrical conductivity property of concrete was one of the properties of concrete that could be used to assess the ability of concrete against penetration of chloride ions. The electrical properties of cement-based materials have been investigated for nearly a century (Shimizu 1928, Calleja 1952, Yoon *et al*. 2015). Theoretical and experimental studies indicate there was a relationship between the electrical conductivity and the permeability of concrete (Ramezanianpour *et al*. 2011, Gulikers 2005, Andrade 1993, Kessler *et al*. 2008). The electrical conductivity of concrete was the expression of the mobility of ions - containing chloride ions - in pore solution of the concrete (Whiting and Nagi 2003). Hence it was expected that there was a logical relation between electrical conductivity and permeability of the concrete. In a specific structure, the more permeable parts had relatively higher electrical conductivity.

But there were limitations in the relationship between conductivity and permeability of concrete. Conductivity of the concrete samples depended on the both properties of the capillary pore structure and the pore solution conductivity (Snyder 2001). As a result, Conductivity test methods are mostly affected by the change in the pore solution conductivity of concrete (Ramezanianpour *et al*. 2011). This variability results in the index obtained not necessarily being proportional to the diffusion coefficient. For example, a concrete containing a low-alkali cement should exhibit a lower resistivity even when it has the same microstructure as one produced by using a high-alkali cement (Snyder *et al*. 2003, Taylor 1987). This is one of the commonly cited limitations in utilizing conductivity methods to assess diffusive transport in cement based materials (Ramezanianpour *et al*. 2011). However, it does not seem to apply for the RCMT method as this test directly measures the chloride ingress into concrete specimen. In the methods proposed by Streicher and Alexander (Streicher and Alexander 1995) and Ramezanianpour *et al*. (Pilvar *et al*. 2015), by saturating the concrete specimens with highly conductive solution, the variability of pore solution becomes much less significant.

In this contribution, based on fundamental electrochemical principles, a modification on electrical conductivity test is proposed. The results of this test are independent of the pore solution conductivity of concrete. This paper deals with the electrochemical principles that led to the development of the modification on electrical conductivity test. It also describes the test method.

2. Theoretical bases

The modified method for measurement of electrical conductivity for evaluation concrete chloride ion permeability is based upon the uniform distribution of ions in steady conditions. This is due to the fact that conductivity and diffusivity are easily measurable in steady state conditions. Nonetheless, in methods which are merely associated with measuring diffusivity and for concrete samples with suitable thickness, a period of one year or longer is required to reach a steady state condition (Zofia and Adam 2013). The driving force for diffusion is the difference in ionic concentration so that a higher gradient leads to increase in flux of ions (Bard and Faulkner 1980). In a steady state condition, the concentration gradient has a constant slope. During the existence of electric field, it acts as the driving force (Spiesz and Brouwers 2013). In steady state conductivity conditions the electric field is constant and the charged ions are uniformly distributed. In a conductivity test on a concrete sample with a chloride solution on one side only, initially chloride ions penetrate into the concrete along a well-defined direction. The steady state condition is achieved once the first line of ions passes through the concrete sample and then the concentration of chloride ions within the pore solution is uniform. In conventional methods, necessary conditions for the steady state is reached after several days, by applying potential difference and driving chloride ions through samples saturated with water. Through saturating the samples by chloride solutions, the steady state is reached at the outset.

In porous materials (such as concrete), where the solid phase effectively acts as an insulator, the speed of diffusion and conduction mainly depends on the tortuosity and the connectivity of the pore structure (Andrade *et al*. 2013, Sun *et al*. 2011). Formation factor, denoted by *F*, is a constant of the material which is defined as the ratio of conductivity (or mobility) of the ion in the pore solution to that in the porous material. This ratio coincides with the ratio of the diffusivity of a single ion in the pore solution to that of the ion in porous material (Eq. (1)) (Atkinson and Nickerson 1984, Garboczi and Bentz 1992).

$$\mathrm{F} = \frac{\sigma_0}{\sigma} = \frac{D_0}{D} \tag{1}$$

Where *F* denotes the formation factor of the porous material, D and D_0 denote the diffusivity of the ion through the porous material and in the pore solution respectively, σ and σ_0 denote the conductivity of the porous material and the pore solution respectively.

Theoretically, the diffusivity of chloride in a porous material can be obtained by measuring the conductivity (Snyder *et al*. 2000). By measuring the conductivity of a regular porous material and its pore solution, the ratio which determines the formation factor is obtained. Then this ratio multiplies the diffusivity of the chloride ion in pore solution to yield the diffusivity of chloride in the porous material.

Although the diffusivity coefficient of concrete can be obtained by measuring the conductivity and using the Nernst-Planck electrochemical equations (Jiang *et al*. 2013), but the validity of this equation is affected by the non-ideal nature of the solutions that are used (Stanish *et al*. 2004). Using the ratio of formation factor resolves this issue, as long as both solutions contain the same ions at the same concentrations i.e., they have the same chloride transport numbers and the same activity coefficients (Streicher and Alexander 1995).

The fact that the entire concrete samples are saturated with a highly conductive solution ensures same conductivity of the pore solution among the samples. The validity of this assumption will be verified later in this article. Conductivity of saturated salted water can be easily measured. The transportable ions such as Na+, K+ and OH- existing in the capillary pores of concrete can raise the conductivity of the pore solution. It is very difficult to physically extract the pore solution of concrete for measuring its conductivity (Buckley *et al*. 2007), and therefore it has not been suitable to be utilised in any of the existing rapid measurement methods. As a result, the value of pore solution conductivity (σ_0**)** should be assumed.

Conductivity of NaCl solution with different saturation levels have been determined experimentally by Streicher and Alexander (Streicher and Alexander 1995). Assessment of similar solutions, including KOH has been conducted in order to examine the effects of their ions upon the conductivity of NaCl solution. It is shown that the growth rate of conductivity in higher concentrations declines, mainly due to increase in the viscosity of the solution. In solutions

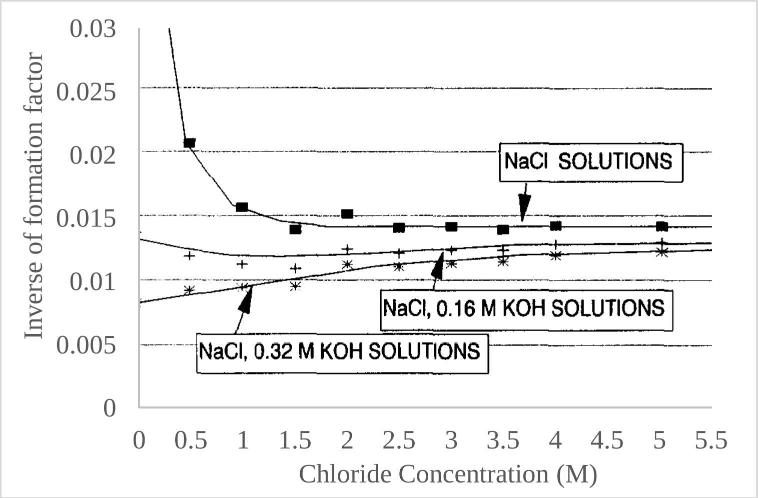

Fig. 1 Inverse of formation factors (Streicher and Alexander 1995)

Table 1 Pore water compositions of OPC and silica fume pastes (Page and Vennesland 1983)

28 days	K+	Na+	OH-	SO42-
OPC	0.63 M	0.27 M	0.83 M	0.31 M
OPC, 20% Silica Fume	0.11 M	0.06 M	0.09 M	0.33 M

containing NaCl and KOH, the existence of NaCl in higher concentrations has the key role in the conductivity. For instance, in a 5 M NaCl and 0.16 M KOH solution, 92% of the total conductivity is attributed to NaCl.

Inverse of formation factor (1/F) has been calculated for different concentrations of NaCl, NaCl & 0.16 M KOH, and NaCl & 0.32 M KOH and have been provided in Fig. 1. It is shown that the conductivity section of formation factor equation ($F=\sigma_0/\ \sigma$), in high concentrations of chloride, is independent from the amount of KOH concentration in pore solution. It is also seen that at low levels of NaCl concentrations, formation factor is more sensitive to the amount of KOH concentration in pore solution.

Page and Vennesland (Page and Vennesland 1983), have measured the ionic concentration of two types of cement paste consisting of Ordinary Portland cement (OPC) and blended cement with 20% silica fume (SF). Table 1 includes the Pore solution Compositions of OPC and SF Pastes. The equivalent mobility’s of K+, Na+ and OH- are 75, 50 and 200 S/cm2/mole, respectively. Therefore the conductivity of the pore solution in OPC paste is almost seven times more than that of the SF paste. This is while the conductivity of the OPC pore solution, once saturated with 5M NaCl solution, would be only 20% more than the pore solution conductivity of the paste having blended cement with SF (Streicher and Alexander 1995).

3. Test method

3.1 Apparatus

The apparatus are the same as described in Test Method ASTM C1760. They consist of two 250 ml cells, contiguous to a central part, which contains the concrete sample. Both cells are tied to the central section, thus compress the silicone rubber collar and clamping the sample. Each cell contains a 5 M NaCl solution. A potential difference of 10 volts applies direct current through the sample via the stainless steel anode and cathode. A data logger reads the flowing current accurately. Since only one current is being measured in this experiment, the apparatus can be used successively for multiple samples. Considering the comparatively short duration of the experiment, the number of flowing ions is small and small cells can be used.

3.2 Test specimens

The apparatus is designed for concrete or mortar samples of 100 mm diameter and 25 mm thickness. Similar apparatus can be designed for different dimensions. Typically, the samples are sliced from cast cylinders or drilled cores. The average thickness of each sample is measured by using a vernier caliper.

Samples are kept in the oven at 50°C for 7 days for being dried. After that, they are vacuum dried for 3 hours, then vacuum saturated in a 5 M NaCl solution for 2 hours, and left to soak in the solution for an additional 18 hours. The drying process is undertaken to ensure uniform saturation with the 5 M NaCl solution and to prevent the dilution. The temperature of 50°C is preferred over 100°C to cause less damage to the samples (Pigeon *et al.* 1993). Although in 50°C the drying intensity is weaker compared to that in 100°C, but in high concentrations, conductivity is less sensitive to small variations in concentration.

The optimum method for preparing the samples is found through trial and error. First, to find the optimum time required for drying the samples, various concrete samples were kept in the oven in 50°C, and their weight were measured in successive days, and the variations in their weights were recorded. After 7 days, variations in the weights of samples were negligible. In the next step, to find the optimum time for keeping the samples in vacuum and saturation, samples were kept in vacuum and saturated for various durations. Then the samples were split in half, and the penetration depth of chloride solution was observed by spraying sample with 0.1 M silver nitrate solution.

3.3 Test procedure

After setting up the cells, the circuit is arranged and the current is measured 1 min after the voltage (10 V) is first applied. This current is recorded as the output of the experiment. For calculating the conductivity of each sample using the potential difference applied, current measured and the dimensions of the sample, Eq. (2) has been used.

$$\sigma = \frac{i}{V} \cdot \frac{t}{A} \tag{2}$$

Where σ is the conductivity of the sample [mS/cm], i is the electric current [mA], V is the potential difference [V], t is the thickness of the sample [cm], and A is the cross section area of the sample [cm^2].

4. Experimental programs

Table 2 Chemical and physical characteristics of OPC and supplementary materials

Chemical Composition* (%)	OPC	SF	CPP
SiO2	21.32	93.6	72.62
Al2O3	4.3	1.3	14.32
Fe2O3	2.2	0.9	1.54
CaO	65.3	0.5	2.24
SO3	2.09	0.1	---
MgO	2.17	1.0	0.82
Na2O	0.36	0.36	2.85
K2O	0.63	0.9	4.9
LOI	0.91	---	2.67

* Chemical Composition is specified according to ASTM C114

In order to examine the performance of the instrument built for measuring the permeability of concrete against chloride ions, 20 different concrete mixtures were used, including ordinary concrete, concrete containing silica fume and concrete containing calcined perlite powder.

4.1 Material

ASTM C150 type I Portland cement was used in all the concrete mixtures. The two pozzolans used in this work, were silica fume (SF) and calcined perlite powder (CPP). Chemical characteristics of mentioned materials are shown in Table 2.

For all mix designs, coarse aggregates were crushed calcareous stone with maximum size of 19 mm and fine aggregates were natural sand. The coarse aggregates have a specific gravity and water absorption of 2510 kg/m^3 and 1.90%, respectively, and the fine aggregates have water absorption of 2.75% and specific gravity of 2570 kg/m^3. Potable water was used for casting and curing all concrete specimens. Also, the Polycarboxylate Ether (PCE) based superplasticizer with specific gravity of 1.05, solids content of 28% and pH of 6.6 was employed to achieve relatively constant workability.

4.2 Mixture proportion and specimen preparation

The variables associated with the mixture proportions used in the samples include binder content of 300, 350 and 400 Kg/m^3, W/C ratio of 0.35 and 0.45, SF 0, 15 and 7.5 percent by cement weight, and CPP 0, 10, 20 and 30 percent by cement weight. Summary of mixture proportion are shown in Table 3.

Slump of all the mixtures, as an indicator of their workability, were kept constant in the range of 90 ± 20 mm using adequate amount of the super plasticizer. All the specimens were casted in three layers; each layer was consolidated on a vibrating table to reduce the air voids. Then, the specimens were kept under a wet towel in the laboratory for 24 hours. After that, they were demolded and cured in lime-saturated water at 23±2°C until the test day to impede possible leaching of $Ca(OH)_2$ from these specimens.

Table 3 Mix proportion of concretes

No.	Mix	Binder (kg/m3)	w/b	Supplementary Material	
				Type	Percentage
1	SF404500	400	0.45	SF	0
2	SF403500	400	0.35	SF	0
3	SF354500	350	0.45	SF	0
4	SF353500	350	0.35	SF	0
5	SF404507	400	0.45	SF	7.5
6	SF403507	400	0.35	SF	7.5
7	SF354507	350	0.45	SF	7.5
8	SF353507	350	0.35	SF	7.5
9	SF404515	400	0.45	SF	15
10	SF403515	400	0.35	SF	15
11	SF354515	350	0.45	SF	15
12	SF353515	350	0.35	SF	15
13	Pe304500	300	0.45	CPP	0
14	Pe304510	300	0.45	CPP	10
15	Pe304520	300	0.45	CPP	20
16	Pe304530	300	0.45	CPP	30
17	Pe303500	300	0.35	CPP	0
18	Pe303510	300	0.35	CPP	10
19	Pe303520	300	0.35	CPP	20
20	Pe303530	300	0.35	CPP	30

5. Results and discussion

In addition to the method developed in this study, which is hereafter referred to as MBCT (Modified Bulk Conductivity Test), two standard test methods RCPT (ASTM 2012a) and bulk conductivity (BCT) (ASTM 2012b), have also been applied to all of the samples. To conduct RCPT and BCT, three 50 mm thick slices were cut from the middle part of 100×200 mm cylindrical specimens of each mixture. After standard preparation and assembling the slices in test cells, a direct current (DC) by a constant 60 V potential difference was applied to them. The average of three test results is used to minimize the discrepancy of the results. Results are shown in Table 4.

As observed, in all samples, for equal amount of cementitious material, the reduction in the water to binder ratio and consequently, the reduction of capillary pores and the condensation of paste, decreases the conductivity and permeability of concrete.

In addition, at a fixed water to binder ratio, reduction in the cement content leads to a decrease in conductivity and the total passed charge. It can be justified by noting that reducing the cement content, reduces the volume of paste in the concrete as compared to solid. Furthermore, solid function as insulators in the structure of concrete, hence as the ratio of the insulator phase of concrete to paste increases, conductivity diminishes.

Table 4 Tests results

No.	Mix	BCT (mS/cm)		RCPT (columbs)		MBCT (mS/cm)	
		28 days	91 days	28 days	91 days	28 days	91 days
1	SF404500	0.254	0.183	5706	4460	1.09	0.88
2	SF403500	0.172	0.119	3807	2556	0.72	0.59
3	SF354500	0.218	0.149	4802	3335	0.98	0.82
4	SF353500	0.150	0.088	3158	1944	0.62	0.43
5	SF404507	0.084	0.047	1918	988	0.61	0.47
6	SF403507	0.060	0.030	1262	629	0.40	0.30
7	SF354507	0.083	0.043	1772	958	0.57	0.44
8	SF353507	0.059	0.027	1243	551	0.36	0.23
9	SF404515	0.056	0.019	1143	417	0.50	0.40
10	SF403515	0.041	0.015	796	319	0.33	0.27
11	SF354515	0.049	0.018	1062	396	0.46	0.35
12	SF353515	0.036	0.014	750	294	0.30	0.19
13	Pe304500	0.303	0.202	6769	5472	1.57	1.40
14	Pe304510	0.249	0.121	5796	2618	1.50	1.20
15	Pe304520	0.207	0.072	4374	1485	1.31	1.03
16	Pe304530	0.148	0.050	3129	1042	1.25	0.81
17	Pe303500	0.179	0.131	3922	3159	1.24	1.09
18	Pe303510	0.162	0.082	3550	2010	1.20	0.95
19	Pe303520	0.141	0.052	3078	1120	1.04	0.83
20	Pe303530	0.125	0.044	2692	810	0.99	0.65

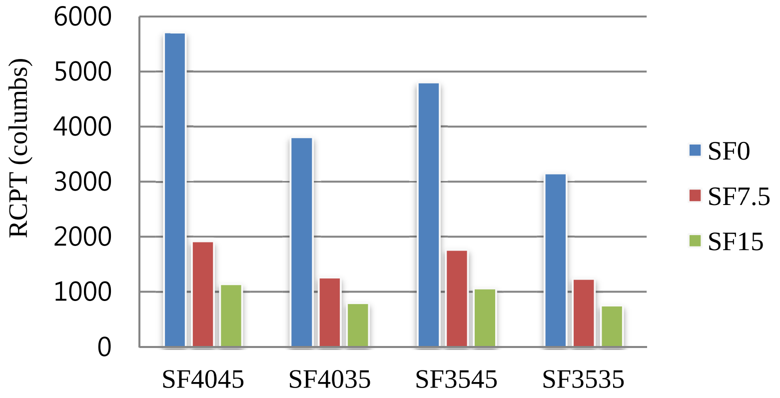

Fig. 2 Results of RCPT for SF series samples, 28 days

As shown in Figs. 2-5, at constant water to binder ratio and cement content, replacing cement with silica fume will remarkably decrease the total passed charge in RCPT and the conductivity of concrete samples. These can be justified by noting that pozzolanic reactions proliferate the tortuosity in the structure of capillary pores and further condenses the pore structure. Furthermore,

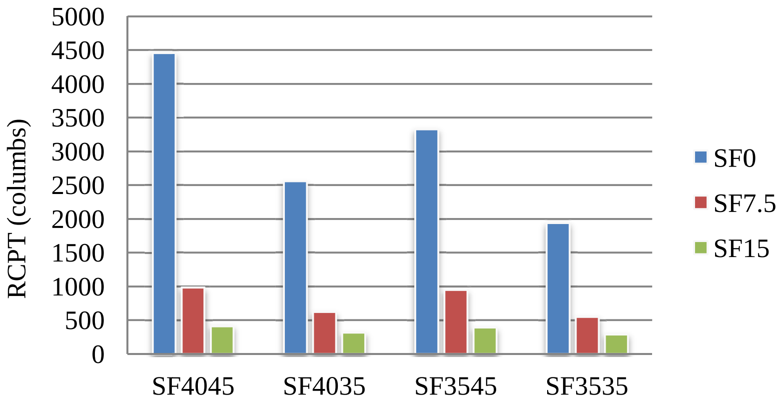

Fig. 3 Results of RCPT for SF series samples, 91 days

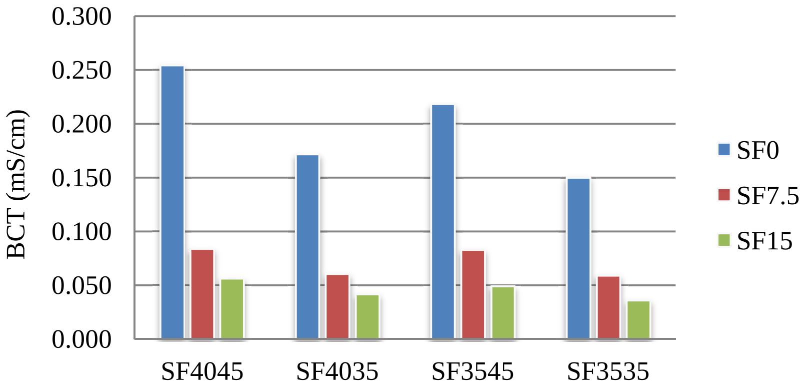

Fig. 4 Results of BCT for SF series samples, 28 days

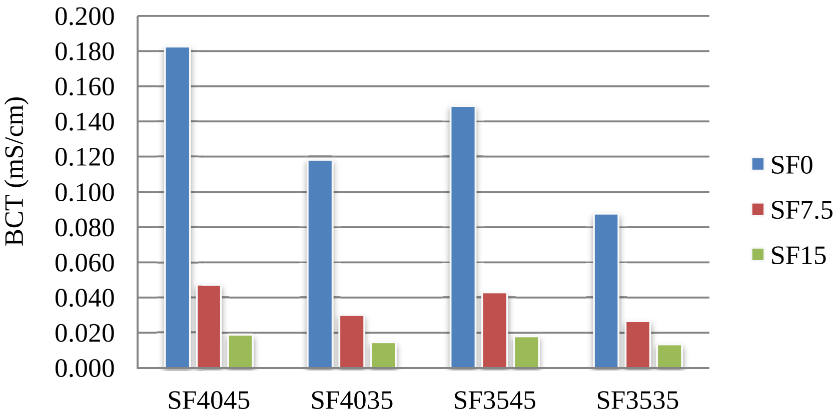

Fig. 5 Results of BCT for SF series samples, 91 days

as the concentration of OH- ions diminishes in most of these reactions, the conductivity of the pore solution diminishes substantially. It is worth mentioning that OH- ions have the key role in the conductivity of the pore solution (Ramezanianpour *et al*. 2014). As a result of these two phenomena, as well as dilution, the conductivity of concrete substantially decreases.

It is noticeable that microstructure of concrete will be affected by the incorporation of silica fume in the mixture. The major influence is the refinement of the pore structure of cement paste. The total porosity may not alter by the addition of silica fume but the large pores are divided into smaller pores and hence changing the microstructure of the cement paste (Ramezanianpour 2014). The effect of various amounts of silica fume on total porosity is studied by Yogendran *et al*. They used mercury porosimetry method.

However, as shown in Figs. 6 and 7, the issue relating to reduction in conductivity has been moderated in the MBCT method. This can be ascribed to the saturation of the samples with 5 M NaCl solutions and the uniformity of the pore solutions conductivity of the different concrete samples. Therefore, it can be argued that this method is less sensitive towards the variations in the

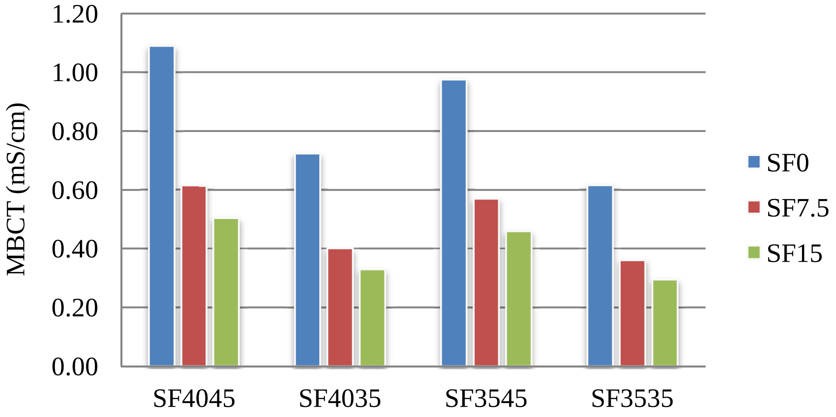

Fig. 6 Results of MBCT for SF series samples, 28 days

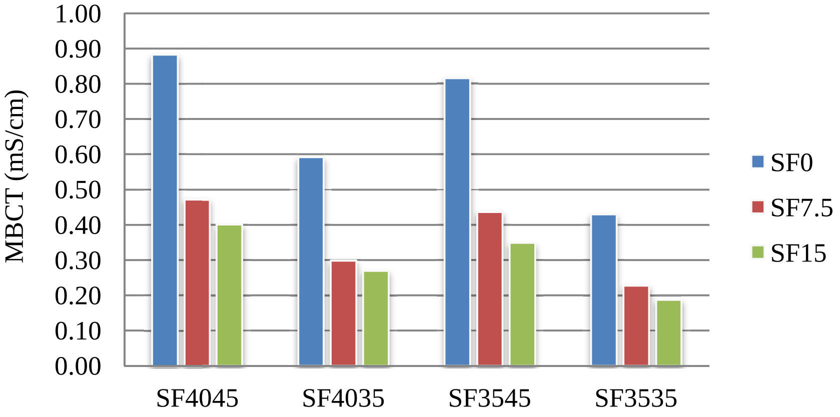

Fig. 7 Results of MBCT for SF series samples, 91 days

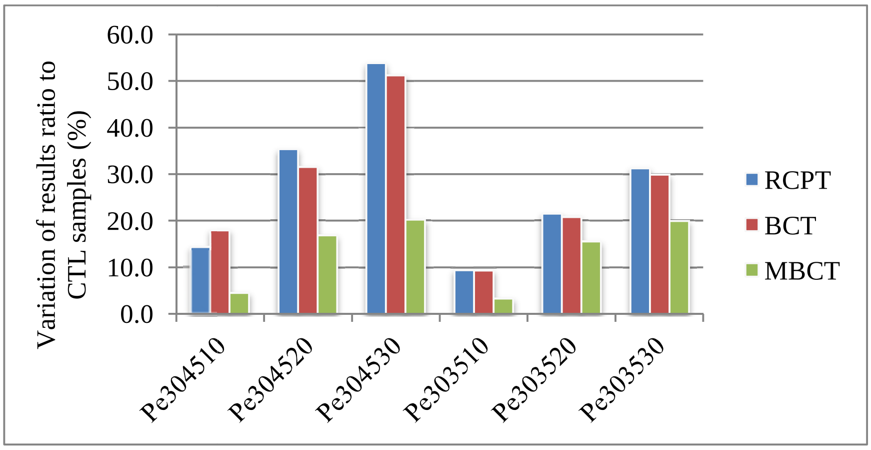

Fig. 8 Variation of results ratio to CTL samples for CPP series samples, 28 days

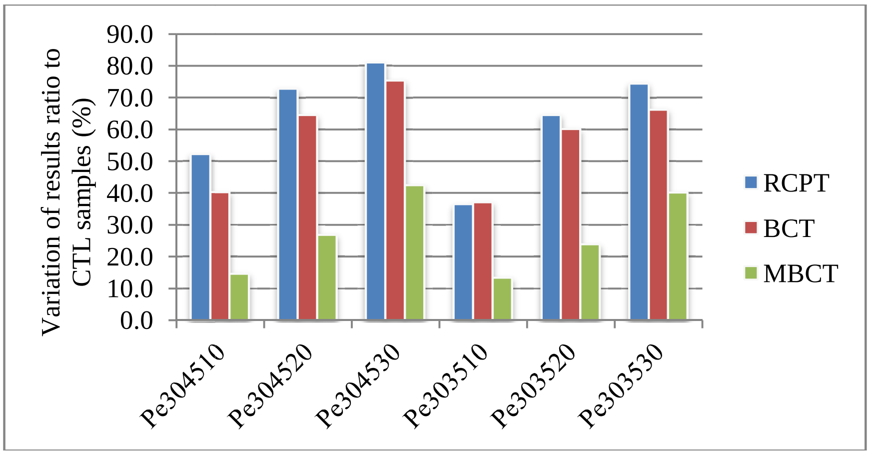

Fig. 9 Variation of results ratio to CTL samples for CPP series samples, 91 days

pore solution conductivity in different concretes.

Figs. 8 and 9 depict the changes observed in the results of the tests in the samples with different replacement of cement by CPP. As observed, the variation of results ratio to control samples associated with the MBCT is more moderate compared to the two other tests.

Replacing cement with CPP of different levels leads to a decrease in the RCPT and bulk conductivity up to half at 28 days. Probably, dilution effect and pozzolanic reactions are the main reasons (Ramezanianpour *et al*. 2014). In fact, substitution of cement causes reduction in the amount of available ions in the pore solution, and pozzolanic reactions can also intensify this occurrence. Furthermore, at the age of 91 days, this reduction is more sharply to less than one fifth in comparison with the control mixtures. It seems that, in addition to dilution effect, the main reason of this great reduction is the pozzolanic reaction which can result in the reduction of the conductivity of pore solution.

Chloride ion permeability classes presented in Table 5 can be used in order to rank different concretes in terms of their chloride ion permeability. This categorization is based on the relationship between these three methods and their associated physical bases.

Table 5 Chloride ion permeability classes according to RCPT, BCT and MBCT

Chloride permeability	RCPT (coulombs)	BCT (mS/cm)	MBCT (mS/cm)
high	> 4000	> 0.16	> 1.1
medium	2000 - 4000	0.08 – 0.16	0.71 – 1.1
low	1000 - 2000	0.04 – 0.08	0.45 – 0.71
very low	100 - 1000	0.004 – 0.04	0.13 – 0.45
negligible	< 100	< 0.004	< 0.13

6. Conclusions

Modified Bulk Conductivity Test (MBCT) that presented in this paper, is one of the fastest methods introduced so far for evaluating permeability of chloride ions and it is based upon robust theoretical bases. Furthermore, the main conclusions which could be drawn from this study are as follows:

- The results of the three tests illustrated that applying SF and CPP reduces the chloride permeability of concrete. Pozzolanic reactions result in the condensation of the structure of concrete as well as blocking its capillary pores.
- In all samples, for equal amount of cementitious material, the reduction in the water to binder ratio and consequently, the reduction of capillary pores and the condensation of paste, decreases the conductivity and permeability of concrete. In addition, at a fixed water to binder ratio, reduction in the cement content leads to a decrease in conductivity and the total passed charge.
- Due to the consumption of OH- ions that ensue in the pozzolanic reactions and consequently the substantial reduction in the conductivity of the pore solution, the permeability indicator of concrete samples incorporating SF and CPP exhibit a substantial reduction when compared to control samples for BCT and RCPT methods. This hints at a shortcoming of these methods in assessing the permeability of concretes with active pozzolans.
- For concretes containing SF and CPP, the MBCT is less sensitive towards the variations in the pore solution conductivity in comparison with RCPT and BCT. This can be ascribed to the saturation of the samples with 5 M NaCl solutions and the uniformity of the pore solutions conductivity of the different concrete samples. It making MBCT a reliable method for assessment of the performance and durability of different concretes containing various supplementary cementitious materials.

References

Andrade, C. (1993), “Calculation of chloride diffusion coefficients in concrete from ionic migration measurements”, *Cement Concrete Res.*, **23**(3), 724-742.

Andrade, C., Prieto, M., Tanner, P., Tavares, F. and Andrea, R. (2013), “Testing and modelling chloride penetration into concrete”, *Constr. Build. Mater.*, **39**, 9-18.

ASTM C1543 (2010), Standard Test Method for Determining the Penetration of Chloride Ion into Concrete by Ponding.

ASTM C1556 (2011), Standard Test Method for Determining the Apparent Chloride Diffusion Coefficient of Cementitious Mixtures by Bulk Diffusion.

ASTM C1202 (2012a), Standard Test Method for Electrical Indication of Concrete's Ability to Resist Chloride Ion Penetration, West Conshohocken Pennsylvania.

ASTM C1760 (2012b), Standard Test Method for Bulk Electrical Conductivity of Hardened Concrete.

Atkinson, A. and Nickerson, A.K. (1984), "The diffusion of ions through water-saturated cement", *J. Mater. Sci.*, **19**, 3068-3078.

Bagheri, A.R. and Zanganeh, H. (2012), "Comparison of rapid tests for evaluation of chloride resistance of concretes with supplementary cementitious materials", *J. Mater. Civ. Eng.*, **24**(9), 1175-1182.

Bard, A.J. and Faulkner, L.R. (1980), *Electrochemical Methods: Fundamentals And Applications*, Wiley, New York.

Buckley, L.J., Carter, M.A., Wilson, M.A. and Scantlebury, J.D. (2007), "Methods of obtaining pore solution from cement pastes and mortars for chloride analysis", *Cement Concrete Res*., **37**(11), 1544-1550.

Calleja, J. (1952), "Effect of current frequency on measurement of electrical resistance of cement pastes", *ACI J. Proceedings*.

Dhir, R.K., Jones, M.R., Ahmed, H.E.H. and Seneviratne, A.M.G. (1990), "Rapid estimation of chloride diffusion coefficient in concrete", *Mag. Concrete Res.*, **42**(152), 177-185.

Garboczi, E.J. and Bentz, D.P. (1992), "Computer simulation of the diffusivity of cement-based materials", *J. Mater. Sci.*, **27**(8)**,** 2083-2092.

Gulikers, J. (2005), "Theoretical considerations on the supposed linear relationship between concrete resistivity and corrosion rate of steel reinforcement", *Mater. Corros.*, **56**(6), 393-403.

Hooton, R.D. and Karkar, E. (2012), "Specifying fluid penetration resistance of concrete", *International congress on durability of concrete.*

Jiang, L., Song, Z., Yang, H., Pu, Q. and Zhu, Q. (2013), "Modeling the chloride concentration profile in migration test based on general Poisson Nernst Planck equations and pore structure hypothesis", *Constr. Build. Mater.*, **40**, 596-603.

Julio-Betancourt, G. and Hooton, R. (2004), "Study of the Joule effect on rapid chloride permeability values and evaluation of related electrical properties of concretes", *Cement Concrete Res.*, **34**(6), 1007-1015.

Kessler, R.J., Powers, R.G., Vivas, E., Paredes, M.A. and Virmani, Y.P. (2008), "Surface resistivity as an indicator of concrete chloride penetration resistance", *Concrete Bridge Conference*, St. Louis, Missouri.

NT Build 355 (1995), Concrete, mortar and cement based repair materials: chloride diffusion coefficient from migration cell experiments, Nordtest Standards Institution.

Page, C.L. and Vennesland, Ø. (1983), "Pore solution composition and chloride binding capacity of silica-fume cement pastes", *Mater. Struct.*, **16**(1), 19-25.

Pigeon, M., Garnier, F., Pleau, R. and Aitcin, P.C. (1993), "Influence of Drying on the Chloride Ion Permeability of HPC", *Concrete Int.*, **15**(2).

Pilvar, A., Ramezanianpour, A.A. and Rajaie, H. (2015), "New method development for evaluation concrete chloride ion permeability", *Constr. Build. Mater*., **101**(1), 10007.

Poulsen, E. and Mejlbro, L. (2010), *Diffusion Of Chloride In Concrete: Theory And Application*, CRC Press.

Ramezanianpour, A., Motahari Karein, S.M., Vosoughi, P., Pilvar, A., Isapour, S. and Moodi, F. (2014), "Effects of calcined perlite powder as a SCM on the strength and permeability of concrete", *Constr. Build. Mater.*, **66**, 222-228.

Ramezanianpour, A.A. (2014), *Cement Replacement Materials*, Springer.

Ramezanianpour, A.A., Pilvar, A., Mahdikhani, M. and Moodi, F. (2011), "Practical evaluation of relationship between concrete resistivity, water penetration, rapid chloride penetration and compressive strength", *Constr. Build. Mater.*, **25**(5), 2472-2479.

Rupnow, T.D. and Icenogle, P. (2011), "Evaluation of surface resistivity measurements as an alternative to the rapid chloride permeability test for quality assurance and acceptance", Louisiana Transportation Research Center.

Safehian, M. and Ramezanianpour, A.A. (2013), "Assessment of service life models for determination of chloride penetration into silica fume concrete in the severe marine environmental condition", *Constr. Build. Mater.*, **48**, 287-294.

Safehian, M. and Ramezanianpour, A.A. (2015), “Prediction of RC structure service life from field long term chloride diffusion”, *Comput. Concrete*, **15**(4), 589-606.

Shimizu, Y. (1928), “An electrical method for measuring the setting time of portland cement”, *Mill Section Concrete*, **32**(5), 111-113.

Snyder, K. (2001), “The relationship between the formation factor and the diffusion coefficient of porous materials saturated with concentrated electrolytes: theoretical and experimental considerations”, *Concrete Sci. Eng*., **3**(12), 216-224.

Snyder, K., Feng, X., Keen, B. and Mason, T. (2003), “Estimating the electrical conductivity of cement paste pore solutions from OH−, K+ and Na+ concentrations”, *Cement Concrete Res.*, **33**(6), 793-798.

Snyder, K., Ferraris, C., Martys, N. and Garboczi, E. (2000), “Using impedance spectroscopy to assess the viability of the rapid chloride test for determining concrete conductivity”, *J. Res.Natl Inst. Stand. Tech.*, **105**(4), 497-510.

Spiesz, P. and Brouwers, H.J.H. (2013), “The apparent and effective chloride migration coefficients obtained in migration tests”, *Cement Concrete Res.*, **48,** 116-127.

Spragg, R., Villani, C., Snyder, K.A., Bentz, D.P., Bullard, J.W. and Weiss, J. (2013), “Electrical resistivity measurements in cementitious systems: observations of factors that influence the measurements”, *J. Transport. Res. Board*, **2342,** 90-98.

Stanish, K., Hooton, R.D. and Thomas, M.D.A. (2004), “A novel method for describing chloride ion transport due to an electrical gradient in concrete: Part 1. Theoretical description”, *Cement Concrete Res.*, **34**(1), 43-49.

Streicher, P.E. and Alexander, M.G. (1995), “A chloride conduction test for concrete”, *Cement Concrete Res.*, **25**(6), 1284-1294.

Sun, G.W., Sun, W., Zhang, Y.S. and Liu, Z.Y. (2011), “Relationship between chloride diffusivity and pore structure of hardened cement paste”, *J. Zhejiang Univ. Sci*., **12**(5), 360-367.

Tang, L. (2005), “Guideline for practical use of methods for testing the resistance of concrete to chloride ingress”, EU-Project Chlortest, Project No: G6RD-CT-2002, 855.

Tang, L. and Lars-Olof, N. (1993), “Rapid determination of the chloride diffusivity in concrete by applying an electric field”, *ACI Mater. J*., **89**(1), 49-53.

Tang, L., Nilsson, L.O. and Basheer, P.M. (2011), *Resistance of concrete to chloride ingress: Testing and modelling*, CRC Press.

Taylor, H.F. (1987), “A method for predicting alkazi ion concentrations in cement pore solutions”, *Adv. Cement Res.*, **1**(1), 5-17.

Wang, J. C. (2015), “Testing of the permeability of concrete box beam with ion transport method in service”, *Comput. Concrete*, **15**(3), 461-471.

Whiting, D.A. and Nagi, M.A. (2003), “Electrical resistivity of concrete-a literature review”, R&D Serial.

Whittington, H., McCarter, J. and Forde, M. (1981), “The conduction of electricity through concrete”, *Mag. Concrete Res*., **33**(114), 48-60.

Xia, J. and Li, L.Y. (2013), “Numerical simulation of ionic transport in cement paste under the action of externally applied electric field”, *Constr. Build. Mater*., **39**, 51-59.

Yogendran, V., Langan, B., Haque, M. and Ward, M. (1987), “Silica fume in high-strength concrete”, *ACI Mater. J.*, **84**(2), 124-129.

Yoon, I.S., Hong, S. and Kang, T.H. (2015), “Influence of curing condition and carbonation on electrical resistivity of concrete”, *Comput. Concrete*, **15**(6), 973-987.

Zofia, S. and Adam, Z. (2013), “Theoretical model and experimental tests on chloride diffusion and migration processes in concrete”, *Procedia Eng.*, **57**, 1121-1130.

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