

Influence of curing condition and carbonation on electrical resistivity of concrete

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Abstract. The electrical resistivity of air-dried, saturated, and carbonated concretes with different mixture proportions was monitored to evaluate and quantify the influence of the age of the specimen, carbonation, and curing condition. After 28 days of curing, four prepared specimens were stored in a vacuum chamber with 5% CO₂ for 330 days to make carbonated specimens. Four of the specimens were placed in water, and four specimens were cured in air until the end of the experiments. It was observed that the electrical resistivity of the carbonated specimens increased as carbonation progressed due to the decrease of porosity and the increase of hydrated products. Therefore, in order to estimate the durability of concrete, its carbonation depth was used as the measurement of electrical resistivity. Moreover, an increase of electrical resistivity for air-dried and saturated concretes was observed as a function of age of the specimen. From the relationship between chloride diffusivity provided by Yoon *et al.* (2007) and the measurements of electrical resistivity, it is expected that the results will be of significant use in calibrating chloride diffusivity based on regular measurements of electrical resistivity during concrete construction.

Keywords: carbonation depth; chloride diffusivity; curing condition; durability; electrical resistivity

1. Introduction

Measurements of electrical resistivity are considered to be a very attractive method for evaluating the properties of geomaterials and for the quality control of concrete because such non-destructive testing (NDT) is simple, rapid, and cost-effective. In 1912, Schlumberger (Meyer de Stadelhofen 1991) measured the electrical resistivity of subsurface rock bodies to evaluate their physical properties. Shimizu (1928) was a pioneer who used the electrical method for detecting setting time of concrete. The methods of electrical resistivity have now reached the level of practical applications to determine chloride diffusivity and corrosion risk (Hope *et al.* 1985, Andrade *et al.* 1993, Saleem *et al.* 1996, Frederiksen *et al.* 1997, Polder 1997, Andrade *et al.* 2000,

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Tang *et al.* 2012), to locate regions of damage (Chen and Chung 1995, Chung 1995, Fu and Chung 1995, Sugita *et al.* 1995, Bontea *et al.* 2000, Niemuth 2004, Chen and Liu 2008, Pour-Ghaz 2012, Simon and Vass 2012), to estimate moisture content (Gjørsv *et al.* 1977, Tuutti 1982, Schiessel *et al.* 2000, Rajabipour *et al.* 2005, Weiss *et al.* 2012), and to find setting time (Shimizu 1928, Calleja 1952, Gu *et al.* 1994, Gu and Beaudoin 1997, Li *et al.* 2003, McCarter *et al.* 2003, Tumidajski 2005, Wei and Li 2005, Li *et al.* 2007).

Electrical resistivity measurements as NDT in the concrete industry are employed for the following reasons 1) to measure resistivity without damage, 2) to save time and cost, and 3) to obtain the results of the measurements in real time. Fig. 1 shows the classification of the service life of a concrete structure into stages: 1) initiation period and 2) propagation period. In general, the initiation and propagation periods are strongly dominated by chloride diffusivity and current density of reinforcement, respectively, both of which are qualitative indices. However, these experimental data are not easy to obtain on-site. As an alternative to these two indices, electrical resistivity can be measured relatively easily and used as a qualitative index for evaluating the corrosion rate of concrete and eventually predicting its service life. Even so, electrical resistivity has some disadvantages because it is affected by several other factors, e.g. 1) amount of cement paste, 2) a water-cementitious material ratio, 3) curing condition, 4) exposure temperature, 5) chlorides, 6) moisture content, 7) cement type and amount of admixtures, and 8) aggregate type (Liu *et al.* 2010).

The carbonation of concrete is a general phenomenon for most of concrete structures, except for underwater concrete structures, and its direction is from exterior to interior because carbon dioxide enters through the surface of the concrete. The effect of carbonation on the durability of concrete is summarized in Table. 1 (Yoon 2014). Carbonation results in reduction of porosity, which leads to decreased chloride penetration and decreased sorptivity of concrete surface. Therefore, concrete carbonation is a primary factor that causes substantial error in the measurements of electrical resistivity.

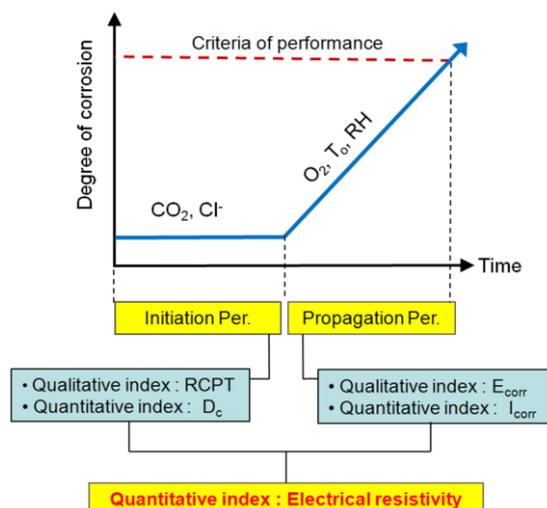


Fig. 1 Modified schematic sketch of steel corrosion sequence in concrete (updated from Tuutti 1982)

Table 1 Effect of carbonation on durability of the concrete(updated from Yoon 2014)

Effect	Consequences for durability of actual structure	Consequences for durability testing
Reduction of alkalinity	Corrosion of reinforcement	Detected with phenolphthalein solution
Decrease of transport coefficient	Decrease in carbonation rate Reduction of chloride and sulfate transport	Misleading results of surface durability test such as initial surface absorption
Decrease of chloride adsorption	Decrease in chloride adsorption Severe risk of reinforcement's corrosion	Determined from ratio of total chloride content to free chloride content
Decrease of electrical resistivity	Questions	Misleading results of resistivity and rest potential Effect on reliability of electrical chloride migration tests
Shrinkage	Cracking	Penetration of harmful substances through microcracks
Crack healing	Increase in molar volume due to formation of CaCO ₃ and lead to crack healing	Leading advantage on effect of the durability of concrete

Table 2. Proportions for concrete mixture

Air (%)	Slump (cm)	w/c	Unit weight (kg/m ³)				Number of specimens		
			Water	Cement	Sand	Gravel	Air-dry curing	Water curing	Carbonation curing
		0.45		411	706	1001	4	4	4
4.5±0.5	15±1	0.50	185	370	720	1021	4	4	4
		0.55		336	732	1038	4	4	4

The objective of this work is to investigate the measurement of the electrical resistivity of concrete with three different curing conditions 1) air-dried 2) fully-saturated and 3) carbonated. It was expected that the experiment results and interpretations would be a relevant means for the evaluation of durability design and calibration factors for the estimation of chloride diffusivity.

2. Experimental methods

2.1 Materials and experimental procedures

A commercial cement, Type I KS L 5201 Ordinary Portland Cement (OPC), was used with a water-cement ratio (w/c) of 0.45, 0.50, and 0.55 as shown in Table 2. Twelve prismatic specimens were fabricated for each w/c and then cured with water for 28 days. The size of each specimen was determined to be 100 mm (L) × 100 mm (W) × 200 mm (H) such that the spacing of the electrodes was much smaller than the height of the materials. The curing temperature was 20°C. After 28

days of water curing, three different curing conditions, i.e., 1) air-dry 2) water and 3) special conditions were applied to accelerate the carbonation of the concrete specimens. Testing with three different curing conditions was intended to investigate the change of electrical resistivity due to water content and the carbonation of concrete.

2.2 Carbonation of specimen

After 28 days of water curing were completed, four of the specimens were exposed in an accelerating carbonation chamber at a temperature of 20°C, relative humidity of 65%, and 5% CO₂ in order to make carbonated concrete. A 1% phenolphthalein-alcohol solution was sprayed on the fracture of the specimens, and a Vernier caliper was employed to measure the depth of carbonation of each specimen.

Since carbon dioxide from air can enter concrete and react with calcium hydroxide to form water and calcium carbonate, the water created by the reaction can significantly influence the measurements of electrical resistivity. Therefore, in order to make uniform water content in concrete regardless of the reaction process, the carbonated specimens first were stored in vacuum chamber at a pressure of 50 kPa for eight hours after which they were fully saturated in water for three hours before the electrical resistivity was measured.

2.3 Electrical resistivity of concrete

It is important to prepare the specimen with the same conditions before testing because the electrical resistivity of concrete is significantly sensitive to both moisture and temperature (Millard 1991; Millard and Gowers 1992). Before the electrical resistivity measurements were made, the concrete specimens were preconditioned as follows 1) water was sprayed on the surfaces of the air-dried specimens and 2) surface water was removed from the saturated specimens. The four-electrode method, known as the Wenner four-pin method, was developed initially for conducting soil resistivity tests by the U.S. Bureau of Standards (Wenner 1916). Fig. 2 shows a schematics diagram of the surface resistivity test used for the concrete specimens in this study. In this method, the two outer electrodes are for current injection, and the two inner electrodes are used to measure the voltage drop due to the resistance of concrete. For an electrode spacing of a , the resistivity of concrete (ρ) can be obtained by using the Ohm's law

$$\rho = \frac{2\pi aV}{I} \quad (1)$$

where V is the voltage drop, and I is the current.

A four-pin resistivity meter, i.e., a Resipod resistivity meter (Swiss PROCEQ Company), was used to measure the electrical resistivity of concrete specimens. For each specimen, four separate measurements were made on four different surfaces. Spacing of a is 40 mm.

3. Experimental results and discussion

3.1 Effect of the age of the specimen

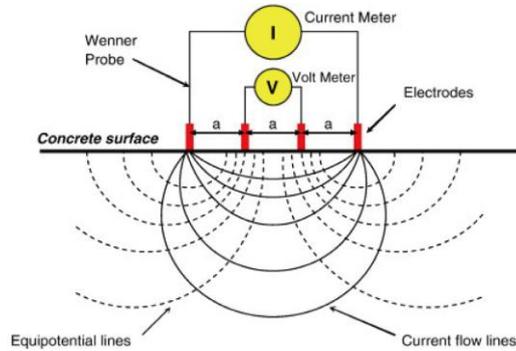


Fig. 2 Electrical resistivity measurements of concrete (Wenner method)

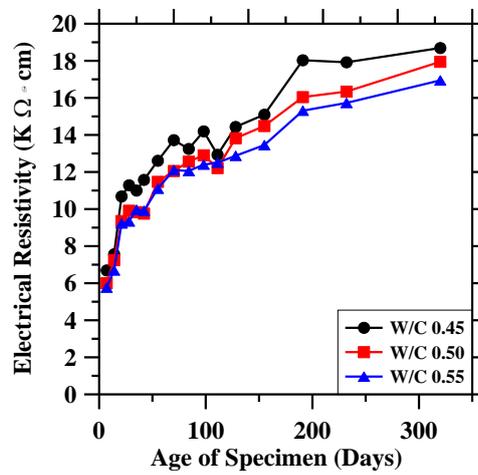


Fig. 3 Electrical resistivity measurements of saturated concrete

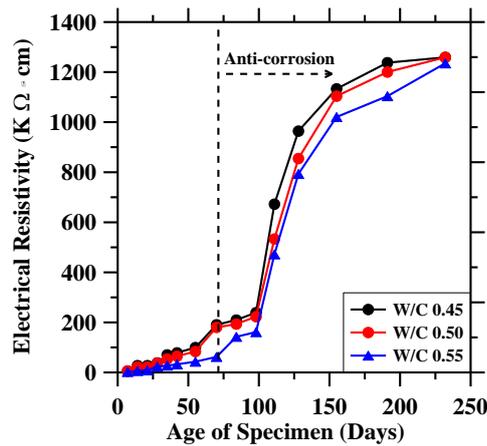


Fig. 4 Electrical resistivity measurements of air-dried concrete

Fig. 3 describes the electrical resistivity measurements of a saturated specimen over a period of time. A gradual increase in electrical resistivity was observed for the greater age of the specimen.

At an early age, there are no differences in the electrical measurements among the different pastes, but it was observed that the mixture that had the lowest w/c ratio had the highest electrical resistivity at the end of experiments. The primary reason should be that the paste that has the lowest w/c ratio has more hydration products and less porosity than the other two mixtures.

Fig. 4 shows the measurements of the electrical resistivity of air-dried concrete. Until 100 days of air-dried curing, it was observed that resistivity increased gradually as the age increased. However, the electrical resistivity increased dramatically from an age of 100 days to the completion of the experiment. The electrical resistivity measurement at the end of the experiment was approximately 1400 KΩ·cm. According to guideline value provided by RESI (2002), corrosion is very low if the electrical resistivity is greater than 12 KΩ·cm. Therefore, it is expected that environment for anti-corrosion is created after 70 days of air-dried and saturated curing in this experiments.

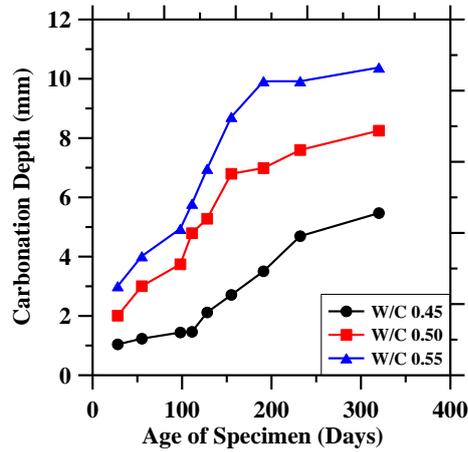


Fig. 5 Carbonation depth of concrete specimen

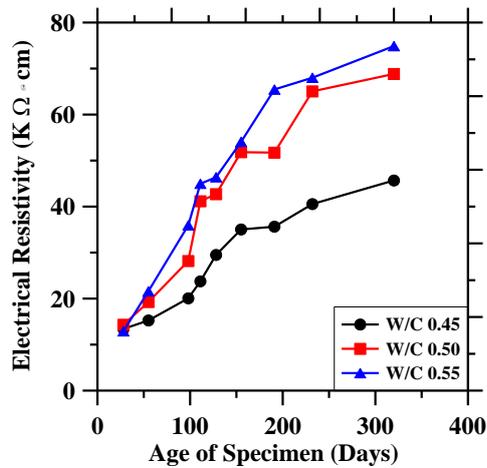


Fig. 6 Electrical resistivity of carbonated concrete

3.2 Influence of carbonation of concrete on electrical resistivity

Fig. 5 presents the change of carbonation depth over a period of 330 days. It was observed that the carbonation depth for the highest w/c ratio was the highest among the three different w/c ratios, and the rate of change of the carbonation depth gradually decreased with the increased age of the specimen.

Fig. 6 shows the average of four measurements of electrical resistivity on carbonated concretes. The increasing trend of electrical resistivity of the carbonated specimens was exhibited because the increase in the carbonation depth of the concrete resulted in a decrease of porosity (De Ceukelaire and van Niewwenburg 1993). In addition, two other reasons for the increased resistivity of specimens were that there was an increase in hydrated products and a change in the pore structure as time increased (Yoon 2013). At 28 days, there were no clear differences of electrical measurements among three w/c pastes, but the rate of electrical resistivity gradually decreased with time. A comparison of the carbonated concrete in Fig. 6 with the non-carbonated specimens in Fig. 3 and Fig. 4 shows that electrical resistivity clearly was influenced by carbonation. The corrosion rate became very low after 50 days of carbonated curing because the electrical resistivity exceeded 12 KΩ·cm.

3.3 Influence of water in the pores on electrical resistivity

The measurement of electrical resistivity is known to be strongly influenced by the amount of water in the materials. According to Buenfeld *et al.* (1986) and Goni and Andrade (1990), the electrical resistivity of water in the pores is about 5×10^{-2} KΩ·cm. According to Osterminski *et al.*'s (2012) experimental results, completely dried concrete does not allow ions or charges to move. Therefore, a small amount of pore water in concrete can lead to high conductivity and low resistivity. Fig. 7 shows the relationship between the electrical resistivity of the specimens and the volumetric fraction of capillary water. The volumetric fraction of capillary water is the same as the degree of hydration. The amount of water in the pores (or degree of hydration) was estimated by the hydration model proposed by van Breugel (1991) without consideration of environmental conditions, i.e., forced evaporation and relative humidity. Fig. 7 shows that the maximum volumetric fraction of water was approximately 0.6 and that the ratio of the electrical resistivity of air-dried concrete to that of saturated concrete decreased dramatically as the amount of water in the pores increased. The relationship between the electrical resistivity ratio of concrete and the volumetric fraction of capillary water in the pores was expressed in Eq. (2). In particular, the electrical resistivity ratio of air-dried to saturated concrete is very sensitive to the amount of water in pore. A sudden decrease in the resistivity ratio from 0.3 to 0.45 was observed. However, a gradual decrease of the ratio of air-dried to saturated concrete was observed as a function of the volumetric fraction of capillary water in the pores between 0.45 and 0.6. From these observations, it can be concluded that water in concrete significantly influences its electrical resistivity and its relationship can be expressed as follows

$$\rho_{air} = 1.822 \times 10^4 \exp \left[-17.079 \left(\frac{V_{water}}{V_{pore}} \right) \right] \cdot \rho_{sat} \quad (2)$$

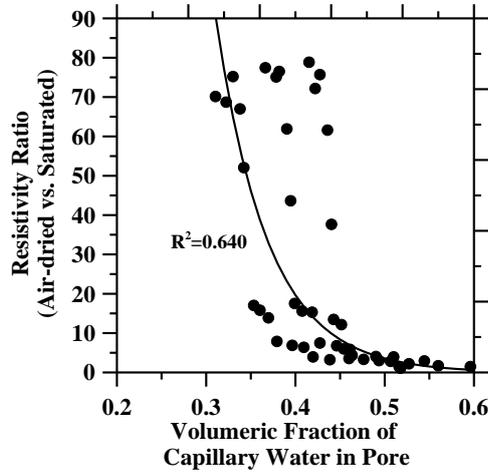


Fig. 7 Relationship between the electrical resistivity of concrete and the volumetric fraction of capillary water in the pores

3.4 Relation between electrical resistivity and chloride diffusivity

Electrical resistivity as well as chloride diffusivity can be of significant use in designing durable concrete structure because the electrical resistivity of concrete is inversely proportional to its chloride diffusivity. The following Nernst-Einstein Equation provides the general relation between the electrical resistivity and chloride diffusivity of the materials (Gjørv 2009)

$$D_i = \frac{R \cdot T}{z \cdot F} \cdot \frac{t_i}{\gamma_i \cdot c_i \cdot \rho} \quad (3)$$

where D_i is the diffusivity of ion i , R is the ideal gas constant, T is absolute temperature, z is ionic valence, F is Faraday constant, t_i is the transfer number of ion i , c_i is the activity coefficient for ion i in the water in the pores, and ρ is electrical resistivity.

Because most of factors in Eq. (3) are constants, it can be expressed more simply using a constant temperature and given moisture conditions as follows

$$D_{cl} = \frac{k_{cl}}{\rho} \quad (4)$$

where k_{cl} is a constant.

Fig. 8 shows the relationship between the electrical resistivity of the specimen with three w/c mixtures and chloride diffusivity provided by Yoon *et al.* (2007). A straight line can be obtained with Eq. (5) for all three w/c mixtures, and then k_{cl} is approximately $1.0397 \times 10^{-6} \text{ (K}\Omega \times \text{cm}^3/\text{s)}$.

$$D_{cl} = \frac{1.0397 \times 10^{-6}}{\rho} - 4.709 \times 10^{-9} \quad (5)$$

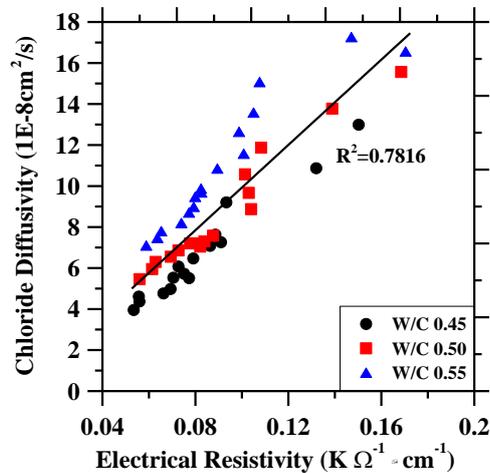


Fig. 8 Relationship between electrical resistivity and chloride diffusivity in concrete

3.5 Environmental effects on electrical resistivity

9 describes the ratio of the electrical resistivity of carbonated concrete to that of noncarbonated, air-dried concrete as a function of age for three different mixtures. The resistivity ratios clearly decreased for 128 days, after which they became constant irrespective of the w/c ratio. The primary reason for this decrease is that the electrical resistivity of air-dried concrete dramatically increased after 100 days and then its rate decreased as a function of specimen age until the end of the experiments. It is reasonable to assume that the electrical resistivity of concrete is influenced to a greater extent by amount of pore water than by changes in the microstructure of the concrete.

Fig. 10 presents the ratio of electrical resistivity of carbonated concrete to that of saturated concrete as a function of the age of the specimen for three mixtures. It is noted that the resistivity ratios have similar values at 28 days. The rate of the resistivity ratio increased and then became zero for all three mixtures. Moreover, the electrical resistivity ratio of concrete with high w/c (w/c = 0.55) is the highest among them because carbonated concrete with a high w/c has the lowest porosity (De Ceukelaire and van Nieuwenburg 1993).

Fig. 11 shows the relationship between the ratio of the electrical resistivity of carbonated concrete to that of air-dried concrete and carbonation depth. In general, the resistivity of carbonated concrete is greater than that of air-dried concrete. However, for carbonated, saturated concrete, it was observed that the resistivity of air-dried concrete was less than that of the carbonated concrete. For concrete with w/c ratio of 0.45, the resistivity ratio decreased sharply to approximately 0.05 value at a carbonation depth of 1.5 mm, after which it became constant. To the depth of 5 mm for a w/c ratio of 0.50, it was observed that the ratio of the electrical resistivity of carbonated concrete to that of air-dried concrete decreased and converged to a certain point. For a w/c of 0.55, the resistivity ratio remarkably decreased until the depth of 7 mm, after which it became constant.

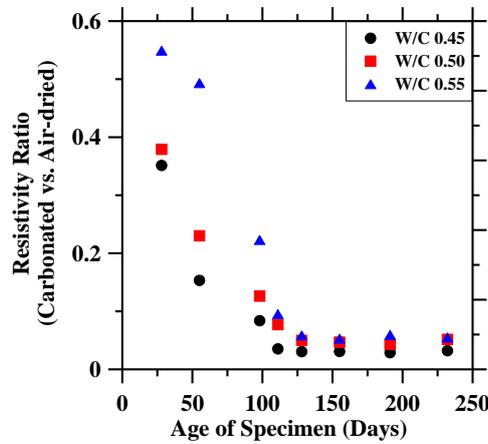


Fig. 9 Ratio of the electrical resistivity of carbonated concrete to that of air-dried concrete as a function of the age of the specimen

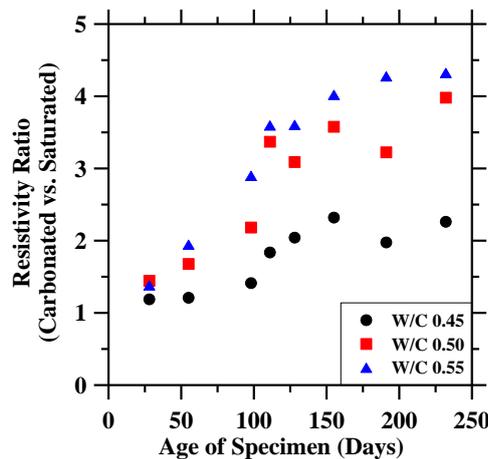


Fig. 10 Ratio of the electrical resistivity of carbonated concrete to that of saturated concrete as a function of age

There are two primary reasons of the effect of carbonation on the electrical resistivity of concrete, i.e., 1) the decrease in the porosity of the concrete results in low conductivity and high resistivity (Simon and Vass 2012) and 2) as carbonation occurs, the concentration of OH^- decreases, which eventually causes low conductivity (Claisse 1988). Fig. 12 describes the relationship between the ratio of the electrical resistivity of carbonated concrete to that of saturated concrete and carbonation depth. It was concluded that the electrical resistivity of concrete increased by a factor of two to three as the carbonation depth in the concrete increased from 3 to 6 mm. The linear relationship between the resistivity ratio and carbonation depth, represented by Eq. (6), is shown in Fig. 12. It is expected that this equation is very useful for determining the calibration factor of carbonated concrete at saturated conditions.

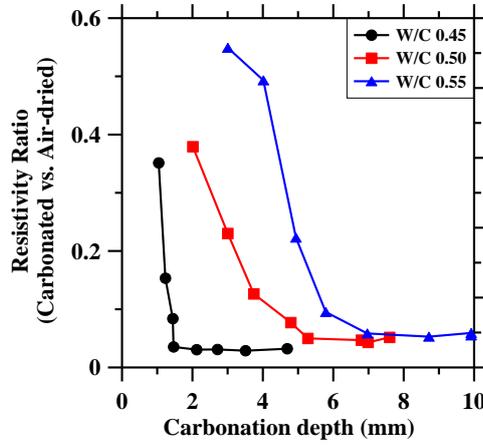


Fig. 11 Relationship between the ratio of the electrical resistivity of carbonated concrete to that of air-dried concrete and carbonation depth

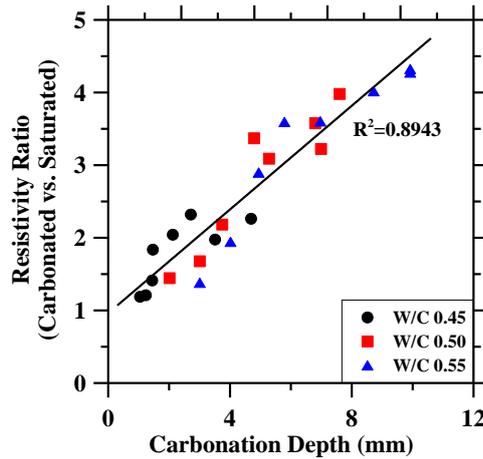


Fig. 12 Relationship between the ratio of electrical resistivity of carbonated concrete to that of saturated concrete and carbonation depth

$$\frac{\rho_c}{\rho_{sat}} = 0.3649d_c + 0.9204 \tag{6}$$

where ρ_c is the electrical resistivity of carbonated concrete under the condition of the saturation ($K\Omega \cdot cm$), ρ_{sat} is the electrical resistivity of non-carbonated, saturated concrete ($K\Omega \cdot cm$), and d_c is the depth of concrete carbonation.

4. Conclusions

Based on the experimental investigation of the electricity resistivity of concretes with three different curing conditions, the following conclusions can be drawn.

- In the saturated condition, the electrical resistivity of the specimens exceeded $12 \text{ K}\Omega \cdot \text{cm}$ and increased continuously after 70 days. This value indicates that the concrete has a good environment to resist corrosion.
- The electrical resistivity of air-dried concrete was significantly different from that of saturated concrete. After 100 days of air-dried curing, the resistivity sharply increased as a function of the age of the specimen until the end of the experiments.
- The ratio of the electrical resistivity of air-dried concrete to that of saturated concrete was very sensitive to the volumetric fraction of water in the pores in the range of 0.3 and 0.6. The resistivity ratio decreased from 0.3 to 0.45. However, it is observed that the ratio gradually decreased as a function of the volumetric fraction of capillary water in the pores between 0.45 and 0.6.
- A linear relationship between electrical resistivity and chloride diffusivity was derived from the experimental results, as shown by the Nernst-Einstein equation. At the saturated condition, this relationship was useful for estimating chloride diffusivity based on the electrical resistivity for use in predicting the service life and for designing its durability.
- The resistivity of carbonated concrete increased as the degree of hydration increased and the size of the pores of the specimens decreased. A comparison of the ratio of the electrical resistivity of the carbonated concrete to that of the air-dried concrete according to the carbonation depth showed that the ratio decreased until it reached a certain point, after which it became constant.
- It was observed that the ratio of the electrical resistivity of carbonated concrete to that of saturated concrete increased as the carbonation depth increased. Thus, it was apparent that the electrical resistivity of concrete was influenced significantly by the depth of carbonation, even when the depth was very small.

Acknowledgments

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