Article

Effect of Water and Chloride Content on Electrical Resistivity in Concrete

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Abstract: Since electrical resistivity of concrete can be measured in a more rapid and simple way than chloride diffusivity, it should be primarily regular quality control of the electrical resistivity of concrete which provides the basis for indirect of quality control of concrete durability during the concrete construction. If this is realized, the electrical resistivity of concrete can be a crucial parameter to establish maintenance strategy for marine concrete structures. Electrical resistivity of concrete is important to estimate two processes involved in corrosion of reinforcement: initiation (chloride penetration) and propagation (corrosion rate). The resistivity of concrete structure exposed to chloride indicates the risk of early corrosion damage, because a low resistivity is related to rapid chloride penetration and to high corrosion rate. Concrete resistivity is a geometry-independent material property that describes the electrical resistance, which is the ratio between applied voltage and resulting current in a unit cell. The current is carried by ions dissolved in the pore liquid. While some data exist on the relationship between moisture content on electrical resistivity of concrete, very little research has been conducted to evaluate the effect of chloride on the conduction of electricity through concrete. The purpose of this study is to examine and quantify the effect of pore water and chloride content on surface electrical resistivity measurement of concrete. It was obvious that chloride content had influenced the resistivity of concrete and the relationship showed a linear function. That is, concrete with chloride ions had a comparatively lower resistivity. Chloride can lead to underestimate the electrical resistivity of concrete. Conclusively, this paper suggested the quantitative solution to depict the electrical resistivity of concrete with various chloride contents.

Keywords: chloride penetration; pore water; electrical resistivity; service life; concrete durability

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1. Introduction

Electrical resistivity in concrete is a reversed function of conductivity and is related to diffusivity of ion in pore [1]. Measurement of electrical resistivity is 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 [2]. Particularly, electrical resistivity can be classified into two stages of durability as proposed by Tuutti [3] which are before and after steel corrosion and thus can be used as the barometer of durability during latent period relating to micro structure of concrete as well as corrosion progress period [4-6]. Electrical resistivity is nondestructive evaluation technology that will not cause any damage to the structure and has many advantages including cost reduction, time reduction, real-time data monitoring and simple method [7-9]. However electrical resistivity measurement has many factors causing data interference. And chloride and water content in concrete may have effect on electrical resistivity [10]. Even so, electrical resistivity has some disadvantages because it is affected by several other factors, e.g.: (i) amount of cement paste, (ii) a water-cementitious material ratio, (iii) curing condition, (iv) exposure temperature, (v) chlorides, (vi) moisture content, (vii) cement type, and volumetric fraction of cement paste, (viii) type and amount of admixtures, and (ix) quality and volumetric fraction of aggregate [9]. When the current is applied, electric field is dependent on chloride content that has effect on pore water transfer [11-12] and thus it's necessary to monitor the data on change in electrical resistivity of concrete containing various chloride contents over time.

Meanwhile, the electrical conductivity is not caused by the binding of electrons in an electrolyte solution but depends on the movement of charges. The resistance of the electrolyte solution is highly dependent on the concentration, while distilled water is generally an insulator and seawater is considered a high conductor [13]. Thus, the electrical resistivity of concrete with chloride ions is low, and the high chloride concentration has been reported to have a greater effect on electrical resistance than water content [14]. However, it is rare to study the change in the electrical resistivity of concrete due to the effect of chloride ion and internal water content.

Since the electrical resistivity is closely related to the porosity of the concrete, it is possible to judge the resistance to chloride penetration as shown in Table 1. However, only the correlation between the durability criteria and electrical resistance was presented in terms of chloride penetration, and the change in electrical resistivity due to the presence of chloride ion was not illustrated in concrete. This paper is intended to evaluate the variation characteristics of electrical resistivity depending on chloride content and water content in concrete. The variation of electrical resistivity was examined over time after mixing chloride ion in the concrete with various w/c ratios.

Table 1. Chloride ions penetrability [1]

Chloride ion penetrability	100mm ×200mm Cylinder (KΩ·cm)	150mm ×300mm Cylinder (KΩ·cm)
High	< 12	< 9.5
Moderate	12 ~ 21	9.5 ~ 16.5
Low	21 ~ 37	16.5 ~ 29
Very low	37 ~ 254	29 ~ 199
Negligible	> 254	>199

2. Experiment Program

2.1. Preperation of samples

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. For chloride contaminated specimen sodium chloride was mixed with mixing water, 0%, 0.5%, 1.0%, 1.5% and 2.0% by weight of cement. The specimen was submerged in same salt water as sodium chloride-mixed water used when producing initial specimen till measuring. 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 curing, and 3) pre-mixed chloride. Testing with the three types conditions was intended to investigate the change of electrical resistivity due to water content and the chloride content.

Table 2. Mixing proportion of concrete

w/c	Unit weight (kg/m³)			
	Water	Cement	Sand	Gravel
0.45	185	411	706	1001
0.50	185	370	720	1021
0.55	185	336	732	1038

2.2. Electirical 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. 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.

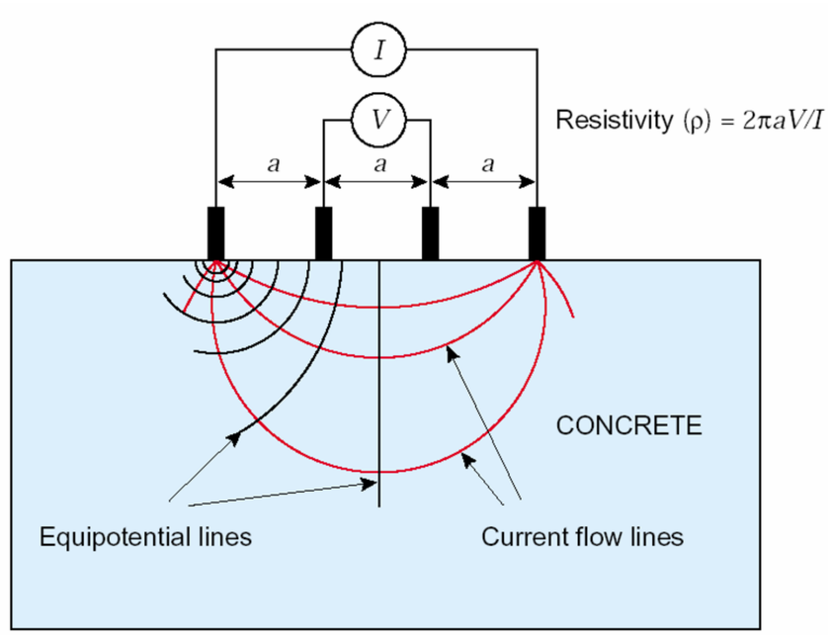
A four-pin resistivity meter, i.e., a Resipod resistivity meter (Swiss PROCEQ Company), was used to measure the electrical resistivity of concrete specimens (Figure 1). For each specimen, four separate measurements were made on four different surfaces. Electrical resistivity is in reverse proportion to the current applied (I) and potential difference (V) is measured on electrode inside and apparent electrical resistivity is measured by following equation according to Ohms law.

$$\rho = \frac{2\pi\, a\, V}{I} \tag{1}$$

where,

ρ : Electrical resistivity of concrete,

a : Interval between electrodes.



1.

Figure 1. Measurement of electrical resistivity measurements in concrete

3. Results

3.1. Effect of the age of the sample

Figure 2 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.

Figure 3 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 driven after 70 days of air-dried and saturated curing.

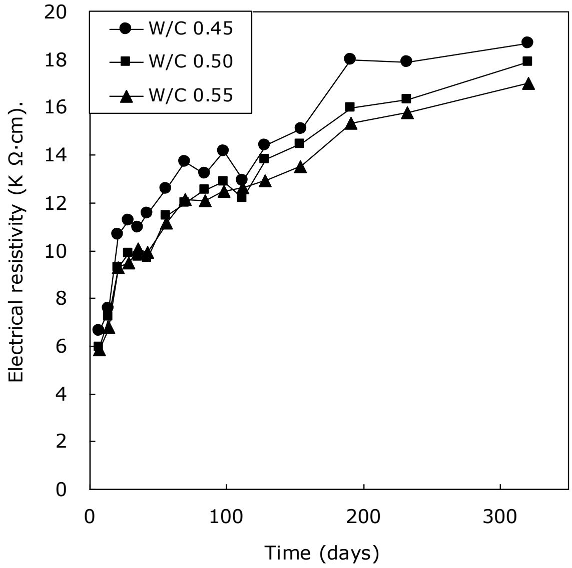


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Figure 2. Electrical resistivity measurements of saturated concrete without chloride

3.2. Effect of the pore water of concrete

The measurement of electrical resistivity is known to be strongly influenced by the amount of water in the materials(Figure 4). According to Buenfeld et al. [4] and Goni and Andrade [10], the electrical resistivity of water in the pores is about 5×10^{-2} KΩ·cm. According to Yoon's experimental results[15], completely dried concrete does not allow ions or charges to move. Therefore, the small amount of pore water in concrete can lead to high conductivity and low resistivity.

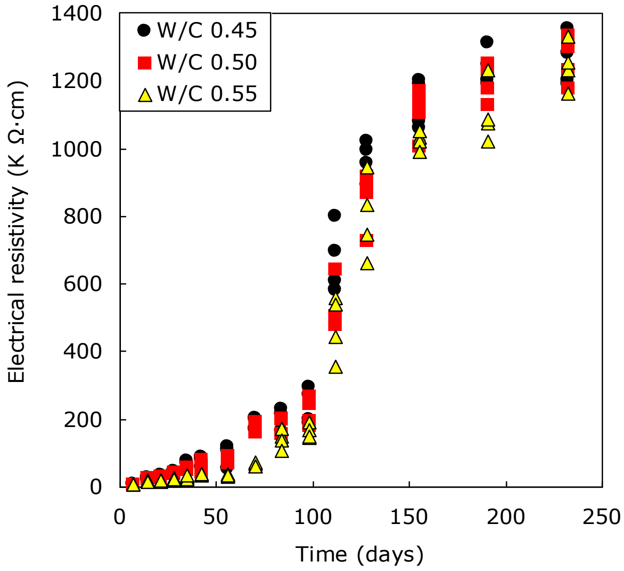

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Figure 3. Electrical resistivity measurements of air-dried concrete without chloride

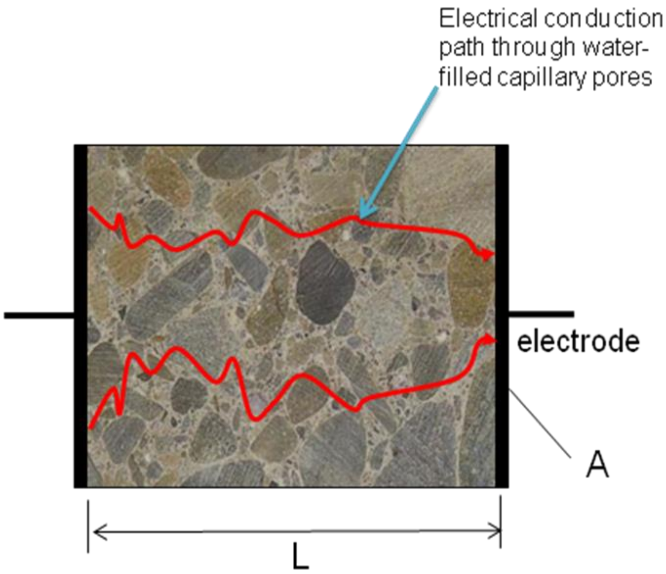

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Figure 4. Effect of pore water on electrical resistivity of concrete

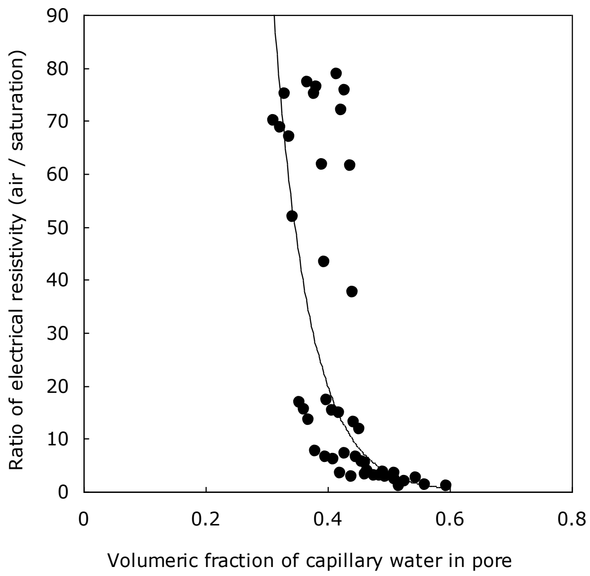

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Figure 5. Relationship between the electrical resistivity of concrete and the volumetric fraction of capillary water in the pores

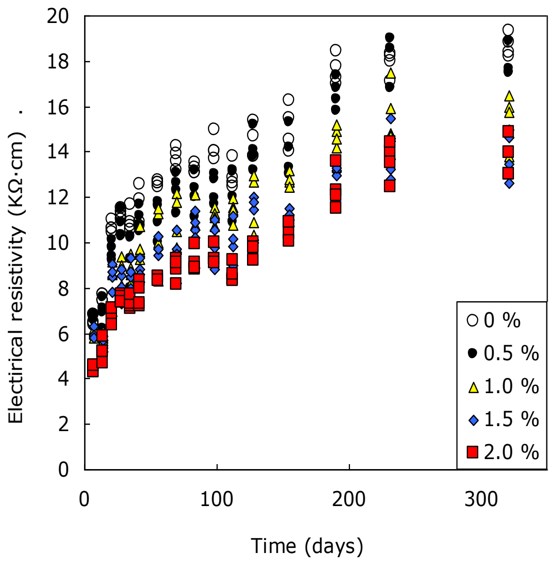
Error! Reference source not found.. 5 shows the relationship between the electrical resistivity and the volumetric fraction of capillary pore water of the specimens. The amount of capillary water in pores was estimated by cement hydration model proposed by van Breugel [16]. The maximum volumetric fraction of the capillary pore 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 pore water 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 capillary 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 capillary pore water in concrete significantly influences its electrical resistivity and its relationship can be expressed as follows:

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

3.3. Effect of chloride content

Figure 6 represents the variation of electrical resistivity of concrete depending on chloride content. The electrical resistivity continued rising due to generation of hydrates and pore structure in line with increasing hydration over time. At early stage, the electrical resistivity of concrete had a low value and the difference depending w/c ratio was insignificant. As the microstructure of concrete was developed with elapsed time, however, electrical resistivity tended to increase. The trend was obvious depending on chloride content. The higher the chloride content, the less the electrical resistivity. According to RESI specific resistance measurement standard and Broomfield [17], the risk of reinforcement corrosion is extremely low when it's 12 KΩ·cm or 20 KΩ·cm. The common value of the two suggestions was 12 KΩ·cm. All concrete excluding the specimen with chloride ion 2.0% and w/c ratio 0.55 failed to meet the value.

According to Presuel-Moreno [18], the electrical resistivity of concrete containing 2% of chloride ion in weight was reportedly reduced1 by the level of 50~60%. The effect of chloride ion on the electrical resistivity of concrete may be considerable because of dry and wetting of the salt water. This study showed that the specimen with 2.0% of chloride ion was 65~71% of concrete without chloride ion and the variation in connection with water-cement ratio was not monitored.



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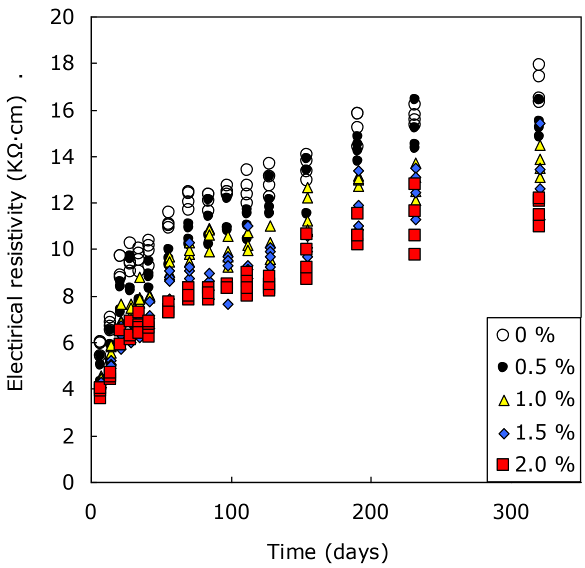
7. (a) w/c 0.45



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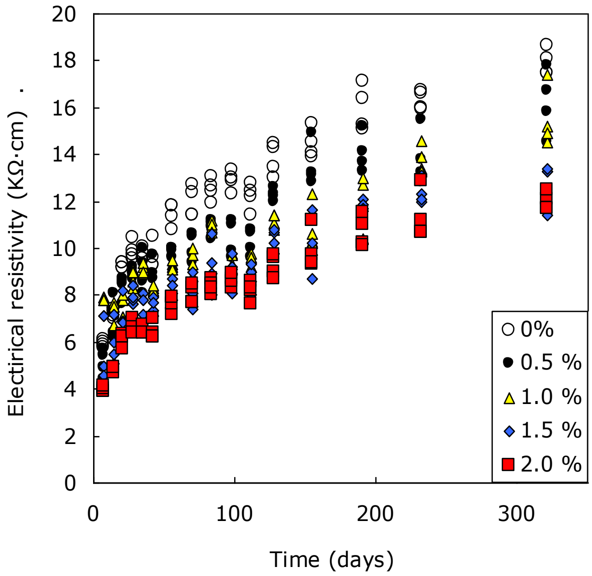
9. (b) w/c 0.50



10.

11. (c) w/c 0.55

Figure 6. Electrical resistivity of concrete with chloride content

3.4. Effect of chloride ion depending time

Figure 7 shows the variation of determinant coefficient as a result of linear regression analysis of electrical resistivity ratio vs. chloride content over time. Though the accuracy was not high, correlation between chloride content and the ratio of electrical resistivity ratio exceeded 0.70, which means the obvious effect of chloride ion on electrical resistivity. At early stage of concrete curing, determinant coefficient was low and then increased over time, however, the effect with w/c ratio was not clear. Low determinant coefficient seemed to be attributable to the irregular variation of electrical resistivity of concrete with chloride content when the hydration of the concrete has not to be activated in earnest at early time.

Figure 8 shows the incline of linear regression analysis equation of the electrical resistivity ratio and chloride content with the concrete without chloride content. The gradient of linear regression analysis equation was low at early time, however, it was constant without significant variation from 50 days. That is, decrease in electrical resistivity depending on chloride content was rather low till 50 days and then continued to rise. After 50 days, trend could not be examined. The electrical resistivity of concrete vs. chloride content was insignificant after 50 days and this was attributable to two reasons. First, C-S-H phase and AFm phase which can react with water soluble chloride to form bound chloride are not well developed[19]. At early stage, chloride adsorption is not active because of immature development of the two hydrates. In addition, it is known that chloride can reduce the electrical resistivity of water. Second, chloride can be a cause of the change of the micro-structural characteristics of cementitious materials. In general, sodium chloride increases the pH of pore solution in concrete and increase in alkali content which causes a heterogeneous C-S-H phase [20]. Therefore, chloride leads capillary porosity with large pore space and this can be a cause of low electrical resistivity of concrete. The first reason of chloride ion absorption and the second reason of micro-structure on electrical resistivity of concrete are not consistent. The micro-structure of hardened cementitious material has more influence on electrical resistivity than chloride absorption, however, considering the low gradient at early time and its increase with time.

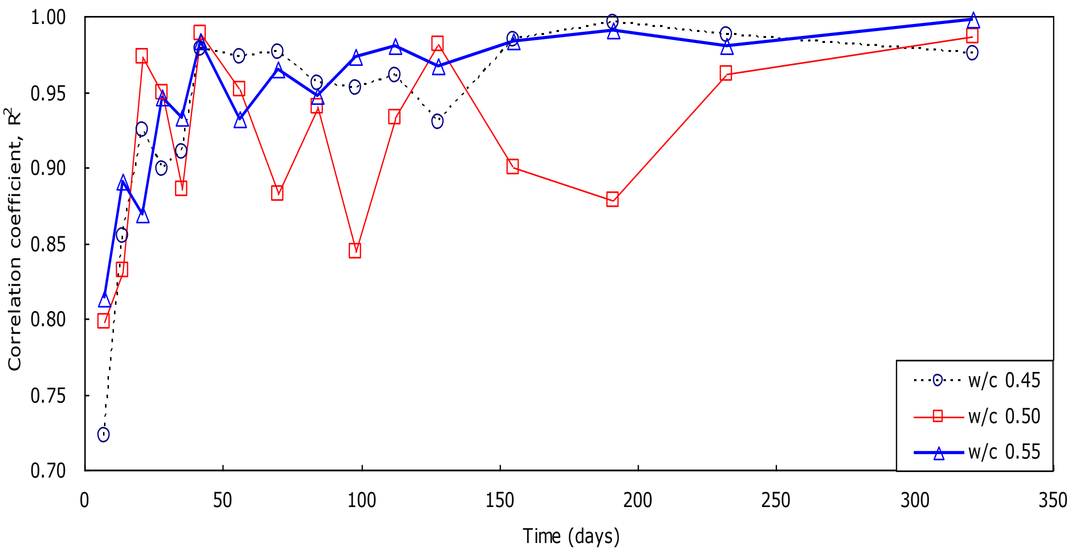


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Figure 7. Correlation coefficient in linear regression deriving from resistivity ratio vs. chloride content

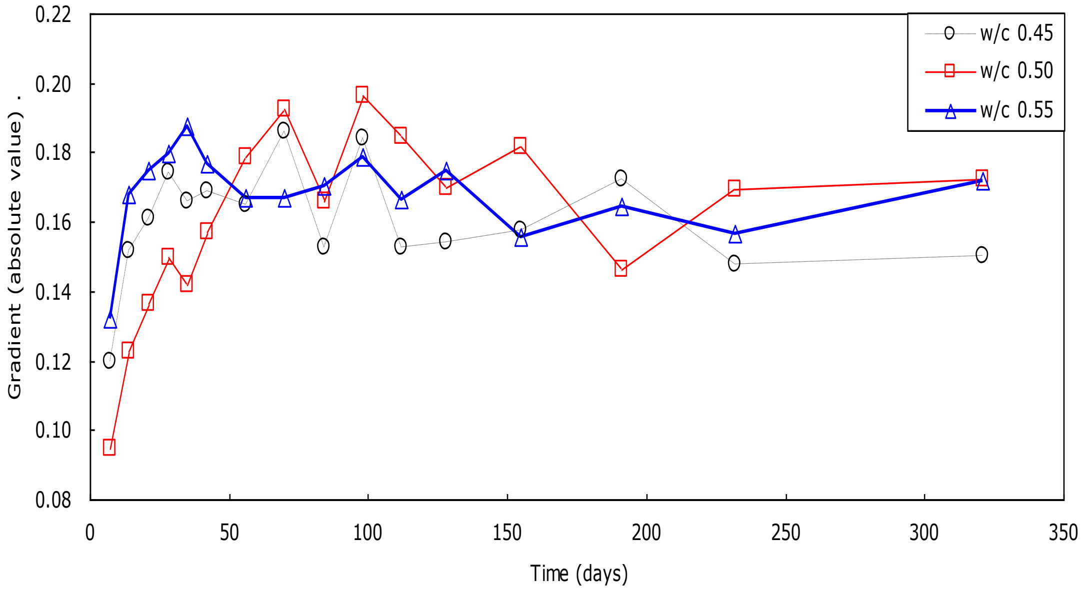

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Figure 8. Gradient in linear regression deriving from resistivity ratio vs. chloride content

3.5. Effect of chloride ion on electirical resistivity

Figure 9 represents the variation of electrical resistivity depending on chloride content. In the figure, the variation of electrical resistivity of concrete with w/c ratio was not monitored, however, the electrical resistivity had decreased for concrete with a high chloride content

Based on the Figure 9, the average electrical resistivity of concrete contaminated with same chloride content was calculated. Figure 10 shows the correlation between chloride content and ratio of average electrical resistivity of concrete with chloride content. The variation with *W/C* ratio was not monitored. It is obvious that chloride content leads to reduce resistivity of concrete. The determinant coefficient was 0.97 which is meaningful in determining the variation electrical resistivity of concrete with chloride ion content as following;

$$\frac{\rho_{Cl}}{\rho_{wat}} = 1 - 0.163C_{Cl} \qquad (3)$$

where, ρ_{Cl} : electrical resistivity of concrete with chloride ion,

ρ_{wat} : electrical resistivity of concrete without chloride ion,

C_{Cl} : chloride ion in concrete (by weight of cement)

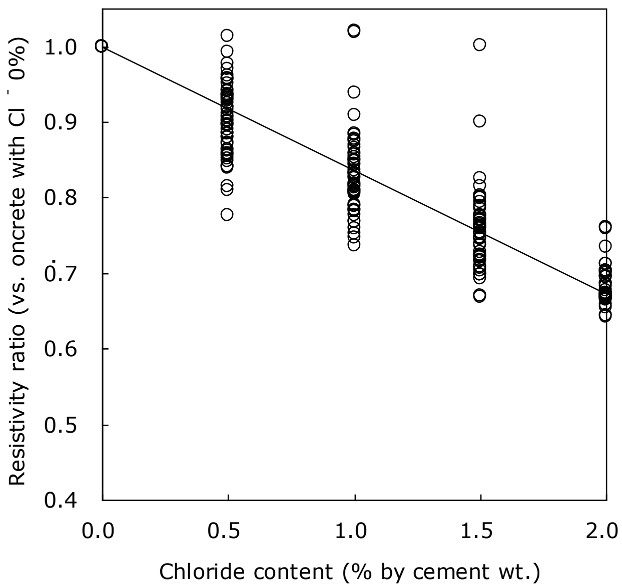

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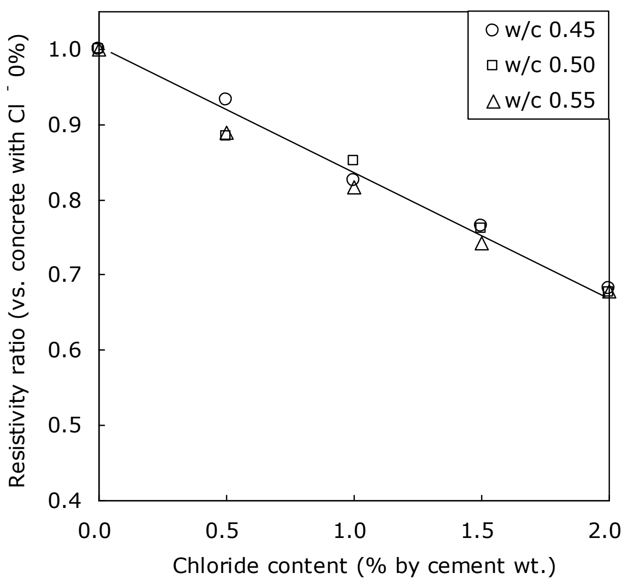
Figure 9. Chloride content vs. resistivity of concrete



15.

Figure 10. Effect of chloride content on resistivity of concrete

4. Conclusions

(1) It was obvious that chloride content leads to reduce resistivity of concrete. Electrical resistivity of concrete kept rising over time and all concrete showed the value 12 KΩ·cm or more except the specimen with 2.0% of chloride ion and w/c ratio 0.55. As a result of viewing the electrical resistivity rate, the value of the specimen with 2% chloride ion was 65 ~ 71% of the specimen without chloride ion.

(2) The electrical resistivity ratio of air-dried to saturated concrete was very sensitive to the amount of capillary pore water. 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.

(3) For the correlation between chloride ion content and electrical resistivity in the specimen without chloride ion, correlation between chloride ion content and electrical resistivity exceeded the determination coefficient 0.70, indicating the obvious effect of chloride ion on electrical resistivity.

(4) The rate of change of electrical resistivity of concrete with chloride was low in the early ages. However, the electrical resistivity showed a more stable trend with no change in the long-term age. These influences are the adsorption of chloride ion and the microstructure development of concrete. The microstructure of the hardened cement paste is more influence on the electrical resistivity than chloride adsorption.

(5) It was observed that the ratio of the electrical resistivity of concrete with chloride to that of saturated concrete without chloride decreased as chloride content increased. Thus, it was apparent that the electrical resistivity of concrete was influenced significantly by chloride content, even when the content was low.

Acknowledgments: The research described in this paper was financially supported by NRF, Republic of Korea(NRF-2018R1D1A1B07042819).

References

1. AASHTO Designation TP 95(2011), Standard Method of Test for Surface Resistivity of Concrete's Ability to Resist Chloride Ion Penetration, American Association of State Highway and Transportation Officials, Washington D.C.
2. Ghosh, P.; Tran, Q. (2015), Correlation Between Bulk and Surface Resistivity of Concrete, *International Journal of Concrete Structures and Materials*, **9** (1), pp.119-132.
3. Tuutti, K. (1982), Corrosion of Steel in Concrete, Swedish Cement and Concrete Research Institute (CBI), Stockholm.
4. Buenfeld, N. R., Newman, J. B., Page, C. L. (1986), The Resistivity of Mortar Immersed in Sea Water, *Cement and Concrete Research*, **16**, pp.511-524.
5. Hope, B. B.; Ip, A. K; Manning, D. G. (1985), Corrosion and Electrical Impedance in Concrete, *Cement and Concrete Research*, **15**, pp.525-534.
6. Simon G.; Tamas K.; Vass, V.(2012), The Electrical Resistivity of Concrete, Concrete Structures, 61-65.Tuutti, K. (1982), Corrosion of Steel in Concrete, Swedish Cement and Concrete Research Institute (CBI), Stockholm.
7. Gjørv, O. E. (2009), Durability Design of Concrete Structures in Severe Environments, Taylor & Francis, New York.
8. Altobat, S.; Maalej, M.; Shaikh, F.U.A (2016), Laboratory Simulation of Corrosion Damage in Reinforced Concrete, *International Journal of Concrete Structures and Materials*, **17** (1), pp.1-9.
9. Liu, Y.; Suarez, A.; Presuel-Moreno, F. J. (2010), Characterization of New and Old Concrete Structures Using Surface Resistivity Measurements, Florida Department of Transportation Research Center, Final Report, Florida.

10. Goni, S.; Andrade, C. (1990), Synthetic Concrete Pore Solution Chemistry and Rebar Corrosion Rate in the Presence of Chlorides, *Cement and Concrete Research*, 20, pp.525-539.
11. Millard, S. G. (1991), Reinforced Concrete Resistivity Measurement Techniques, *Proceedings of Civil Engineers*, Part2, 91, pp.71-78.
12. Millard, S. G.; Gowers, K. R. (1992), Resistivity Assessment of In-Situ Concrete: the Influence of Conductivity and Resistivity Layers, *Proceedings of Civil Engineering Structures and Building*, **94**, pp.389-395.
13. Atkins, P. W., and De Paula, J. (2006), Physical Chemistry, 8th edition, Oxford University Press, Oxford.
14. Saleem, M.; Shameem, M.; Hussain, S. E.; Maslehuddin, M.(1996), Effect of Moisture, Chloride, and Sulphate Contamination on the Electrical Resistivity of Portland Cement Concrete, *Construction Building and Materials*, **16** (3), pp.209-214.
15. Yoon, I. S. (2013), Influence of Micro-Structural Characteristics of Concrete on Electrical Resistivity, *Journal of the Korea Institute for Structural Maintenance and Inspection*, **17** (6), pp.122-129.
16. Van Breugel, K. (1991), Simulation of Hydration and Formation of Structures in Hardening Cement-Based Materials, Ph.D Dissertation of Delft University of Technology, The Netherlands.
17. Broomfield, J. P. (1997), *Steel Corrosion in Concrete*, E & FN Spon, London.
18. Presuel-Moreno (2010), Final Report: Characterization of New and Old Concrete Structures Using Surface Resistivity Measurements, Florida Department of Transportation Research Center
19. Yoon, I. S. (2014), Analysis on Adsorption Rate & Mechanism n Chloride Adsorption Behavior with Cement Hydrates, *Journal of the Korea Concrete*, **27** (1), pp.85-92.
20. Dehwah, H. A. F.; Austin, S. A.; Maslehuddin, M.(2002), Effect of Cement Alkalinity on Pore Solution Chemistry and Chloride Induced Reinforcement Corrosion, *ACI Materials Journal*, **99**(3), pp.227-233.