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Mortar Characterization using Electrical Resistivity Method

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모르타르의 전기비저항 특성

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Abstract: Cement based mortars are widely used to improve the soft ground of a dam site, highway construction, and karst voids. The mechanical properties of the mortar are well documented in literature, however very limited work is done on their physical properties such as electrical resistivity which is considered as one of the most important physical property known while improving the soft grounds. In this paper, electrical resistivity of the Portland cement mortars is examined by employing the Wenner technique. Cylindrical specimens with various water/cement ratios (w/c) ranges from 0.35, 0.45, 0.50 and 0.65 were cast and tested. The test results showed that the electrical resistivity of the mortar increases with increasing curing time and decreases with increasing water content and w/c. A reasonable, good relation was found between electrical resistivity and compressive strength of mortar.

Keywords: mortar, electrical resistivity, compressive strength, curing time, water/cement ratios

요 약: 시멘트 모르타르는 고속도로 건설 및 댐 사이트의 연약지반 보강과 석회암 공동의 지반보강에 널리 사용되고 있다. 모르타르의 물리적 성질은 많은 연구 결과로부터 잘 알려져 있지만, 연약지반의 개량 정도를 평가하기 위해서 알아야 할 가장 중요한 물성 중의 하나인 전기비저항에 대해서는 극히 일부의 연구만 수행되어 있다. 이 연구에서는 물과 포틀랜드 시멘트의 배합비(0.35, 0.45, 0.50, 0.65)를 달리하여 원통형의 모르타르 시료를 제작하여, 웨너 배열 방식으로 전기비저항을 측정하였다. 그 결과 모르타르 시료의 전기비저항은 경과시간에 따라 증가하였으며, 함수비와 물/시멘트의 배합비가 증가할수록 감소하였다. 이 결과로부터 모르타르의 전기비저항과 압축강도는 밀접한 관계를 가지고 있음을 알 수 있었다.

주요어: 모르타르, 전기비저항, 압축강도, 건조시간, 물/시멘트 배합비

Introduction

Grouting involves injection of mortar into weak and permeable ground to improve its properties. The mortar hardens over a period of time and makes the ground stronger and less permeable. The properties of grouted ground are controlled by the properties of the materials comprising the mortar mixture and their interactions with the rock or soil mass. Since the mortar can only travel in voids, the permeability and porosity of the rocks and soils to be grouted are important in the selection of the right mortar mixture and the successful grouting operations. Grouting finds a wide field of application in construction, mining engineering structures and karst voids. For example, Grouting is regularly carried out to reduce the permeability and increase the strength of the rock and soil masses in dam foundations and karst voids (Fazeli, 2007). The efficiency of grouting is generally assessed by carrying out in situ permeability and standard penetration test (SPT). However, SPT has one major disadvantage in the sense that it normally causes destruction of grouted columns and also may not be time and cost effective. Geophysical methods seem to be more reasonable alternative which is advantage of nondestructive and time effective. Several nondestructive geophysical methods are available to perform test on grouted area. Browne (1982) formerly studied the

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relationship between corrosion rate and electrical resistivity of concrete and demonstrated that concrete resistivity must be kept below the range of 50 to 100 ohm-m to prevent corrosion of reinforcement steel. The electrical resistivity was also used to evaluate the interface properties between reinforcement steel and concrete that was characterized by interfacial voids and interfacial phases (Fu and Chung, 1998). McCarter (1996) used a Wenner four-electrode system to assess the relative performance of the surface treatment of concrete. The Wenner technique is becoming increasingly popular for measuring resistivity of reinforced concrete to assess the rate of corrosion of the steel reinforcement. The efficiency of this technique was tested by Gowers and Millard (1999) and they found that there are six sources of error in taking resistivity measurements. The focus of this paper is the application of an electrical resistivity method to monitoring the evolution of material properties of cement based mortar. A series of laboratory tests were carried out on mortar specimens. The effects of w/c, degree of saturation and curing time on electrical resistivity and compressive strength of mortar are discussed.

Theoretical Background

Measurement principle

The resistivity method is based on the application of Ohm's law. Electrical current is introduced into the ground by one pair of electrode while potential difference is measured by another pair of electrodes. An electrical resistivity ρ is determined by measuring the potential difference ΔV at a different couple of electrodes as following:

$$\rho = k\frac{\Delta V}{I}, \quad (1)$$

where k is a 'geometric' constant that depends only on the reciprocal positions of the four electrodes, and I is the intensity of the induced current.

Porosity

In cement based mortar, only the pore fluid contributes to the flow of electrical current. Archie (1942) investigated the relationship between the electrical resistivity and porosity of rocks saturated with conducting water. Archie's law may also be applied to cement based mortars

$$F = \frac{\rho}{\rho_0} = \frac{a}{\theta^m}, \quad (2)$$

where F = the formation factor, ρ_0 = resistivity of the conductive component, ρ = the resistivity of composite system, θ = the porosity, and a and m are constants.

All solid phases (aggregate, hydrates and un-hydrated binder) in hydrating mortar are considered as nonconductive components compared with the pore solution. Mortar composite can also be considered as aggregate (nonconductive component) and paste matrix (conductive component). The constants in Archie's law may not be valid for hydrating cement, in which the mortar initially goes from being an unconsolidated liquid suspension toward being a substance with an emerging matrix and decreasing porosity. Not much work is presented so far on Archie's law and cement based mortar.

Ion transport

Electrical current is transported through the mortar by ions. Thus, the conductivity is controlled by the ion concentration (c), the number of charges per ion (z), and the equivalent ionic conductivity (λ). The electrical conductivity (σ) of an aqueous solution can be calculated as follows by summing the contributions for ion j (Prentice, 1991).

$$\sigma = \Sigma_j(|z_j|\lambda_j c_j), \quad (3)$$

Cement chemistry

The ions, we are likely to find in the fluid, can be inferred from the cement chemistry. Hydration of the cement may be divided into five periods (Perez-Pena *et al*., 1989; Michaux *et al*., 1990): pre-induction, induction, acceleration, deceleration and diffusion. The pre-induction period takes place immediately after mixing and lasts for a few tens of minutes while calcium (Ca) and hydroxyl (OH) ions go into the solution. In the induction period little happens except a slow precipitation of semi-crystalline calcium silicate hydrate get (C-S-H) while the Ca^{2+} and OH^- concentrations continue to rise slowly. At start of acceleration periods, the Ca^{2+} concentration reaches the saturation level, and the first hydration reactions begin, with the crystallization of solid calcium hydroxide and the deposition of (C-S-H) get in pores. While the structure is building up, the porosity decreases and the availability of ions and water will be reduced. The start of the acceleration period is approximately 3 hours, and the diffusion period begins after approximately 1 day. From this discussion, it follows that the Ca^{2+} and OH^- ions are the most important from an electrical conductivity point of view. In

Table 1. Chemical composition of cement (%)

Item	CaO	SiO_2	Al_2O_3	Fe_2O_3	MgO	Cl	K_2O	Na_2O	LOI	SO_3
Cement	61.3	21.47	4.32	3.34	2.62	0.01	1.38	0.58	2.03	2.09

Table 2. Physical properties of sand

Sand	Distribution of particle size %					
	Gravel	Sand (0.75 ~ 2.5 mm)	Silt (0.06 ~ 0.002 mm)	Clay	Specific gravity g/cm^3	Uniformity coefficient, U
Standard	0.0	99.9	0.1	0.0	2.65	1.61

addition, significant concentrations of Na^+, K^+ and SO_4^{2-} ions can be found in the cement pore fluid. When hydration starts, the concentrations of Ca^{2+} and SO_4^{2-} decline slowly whereas Na^+, K^+ and OH^- concentrations increase slowly (Christensen *et al.,*2005; Michaux *et al*., 1989). This is the reason why the conductivity of the cement pore water does not remain constant.

Experimental Materials and Test Methods

Ordinary Portland Cement (OPC) ASTM Type-I with a specific gravity of 3.14 and fineness 2996 cm^2/g was used as cementitious material. The chemical composition of cement in percentage by weight of the constituent oxides is shown in Table 1. Standard sand was used as fine aggregate. Physical properties of sand are outlined in Table 2. Normal tap water was used for preparing the mortar. The Mixture proportions of mortar (with w/c ranges from 0.35, 0.45, 0.50 and 0.65) are given in Table 3. Four water/cement ratios (w/c) were used in the mixture proportions. The fresh mortar was produced using a rotating pan type mixer. For each mix, cylindrical specimens of size 100×200 mm were cast using paper mold. After casting, all the specimens were placed in a cool place, then covered with a plastic sheet and wet burlap. The specimens were removed from molds after 24 hour and weighed before curing under moist and dry air. In moist curing, specimens were immersed in water while, in case of dry air curing, the specimens were exposed to air. The temperature in curing was maintained at $23 \pm 2^{o}C$.

In this study, the electrical resistivity of the mortar was measured using the Wenner (1916) technique, consisting of four equally spaced electrodes that are embedded in mortar specimens, having a length of 10 cm and thickness of 0.2 cm. The two outer electrodes induce the measuring current and the two inner electrode measure the resulting potential difference (Fig. 1). The vertical spacing of the electrodes is 4 cm.

Table 3. Mixture proportions by weight of cement for tested mortars

Mixture	w/c	Cement	Sand	C/FA FA = Fine aggregate
A	0.35	1	2	0.5
B	0.45	1	2	0.5
C	0.50	1	2	0.5
D	0.65	1	2	0.5

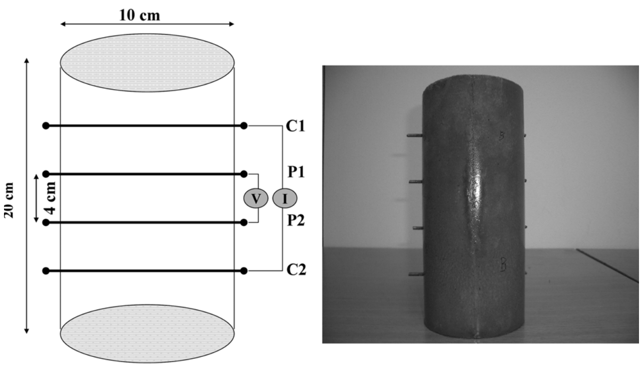

Fig. 1. Experimental setup of Wenner technique for measuring electrical resistivity.

1 mA current is injected using mini OHM (OYO Co). The electrical resistance R is then calculated using Ohm's law assuming that the electric field is one-dimensional

$$R = \frac{\Delta V}{I}, \tag{4}$$

The vertical electrical resistivity ρ is then computed from electrical resistance via

$$\rho = 2\pi a \frac{\Delta V}{I}, \tag{5}$$

where a is the electrode spacing, I is current and ΔV is potential difference. This formula applies in principle only for homogeneous semi-infinite volumes of concrete. However, the applicability of this formula for laboratory specimens has been shown by Millard (1991) and Elsener (1988). From laboratory tests on various mortar specimens, it is shown that true resistivity is obtained within an error of 5 ~ 10 %.

The compressive strength is a key factor determining the mechanical property of mortar and in the early stage, the variation in the strength is quite complicated. The compressive strength of mortar was measured by ASTM C 39. A relationship is developed between the compressive strength and the electrical resistivity of mortar.

Results and Discussion

Effect of water-cement ratio on electrical resistivity of mortar

Water cement ratio is one of the most important parameters of grouting. It has a significant effect on the strength of reinforcement zone. The water cement ratio plays a significant role in developing the microstructure of cement paste and the ionic concentration of its pore fluid. The relationship between the electrical resistivity and water-cement ratio of the mortar specimens is plotted in Fig. 2. The plot shows that mortar specimens resistivity falls sharply with the increase of water-cement ratio. The main reason is that as with the increase in water-cement ratio, which leads to the increase in the pore fluid content of the mortar. The current transmission path became straighter. Thus, the electrical resistivity of mortar admixture decreased.

Effect of degree of saturation on electrical resistivity of mortar

Of all the variables which have an influence on the electrical resistivity of mortar, moisture content is the most significant factor. Mortar specimens were dried from 100 % to 40 % saturation and then resistivity was measured. Fig. 3 shows the variation of the electrical resistivity with respect to the degree of saturation of the tested mortar specimens. The electrical resistivity of the mortar specimens increases when the degree of saturation decreases. The reason for this observation is because with the decrease in the degree of saturation, less pore spaces were filled with pore water. As result, the electrical resistivity increased.

Effect of curing time on electrical resistivity of mortar

Resistivities of mortars specimens were measured, which was continuously moist cured for a month. The relation between the curing time and measured electrical resistivity of mortar is shown in Fig. 4. The result shows that the greatest increase in resistivity occurs in 0.35 w/c ratio. With increase in the curing time, the contents of chemical reaction productions such as calcium silicate hydrate and calcium aluminate

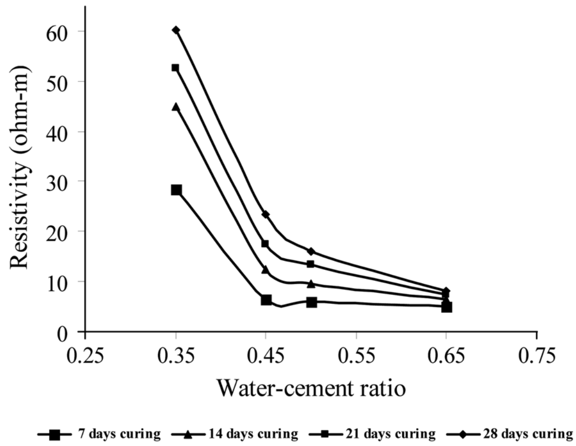

Fig. 2. Effect of water cement ratio on electrical resistivity of mortar.

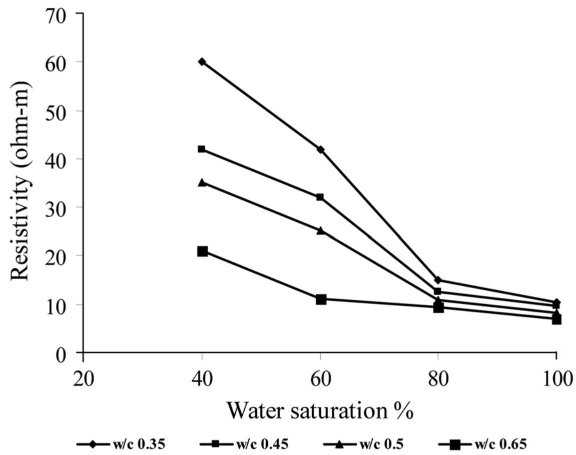

Fig. 3. Effect of water saturation on electrical resistivity of mortar.

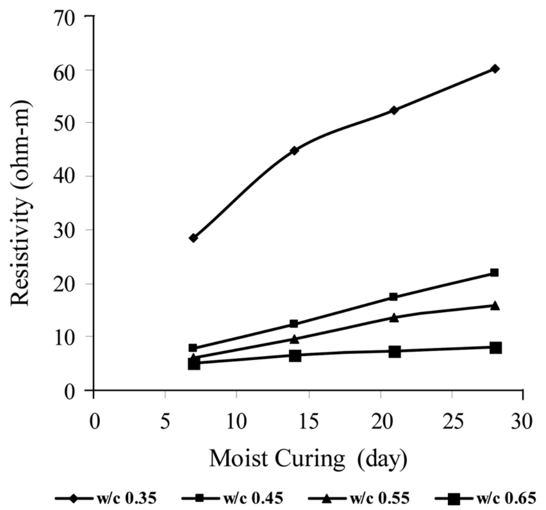

Fig. 4. Effect of curing time on electrical resistivity of mortar.

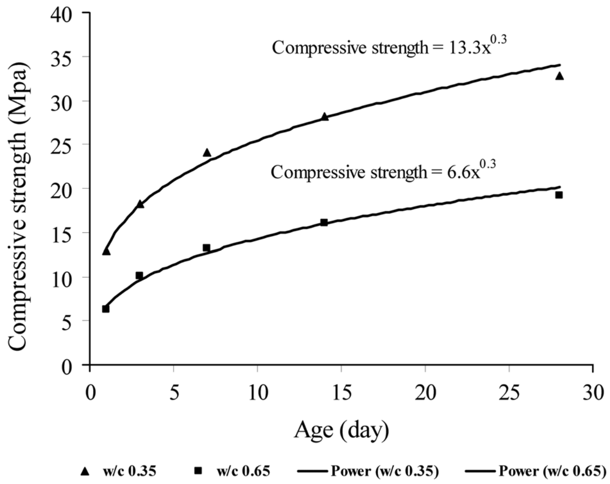

Fig. 5. Development of compressive strength of mortar with w/c and age.

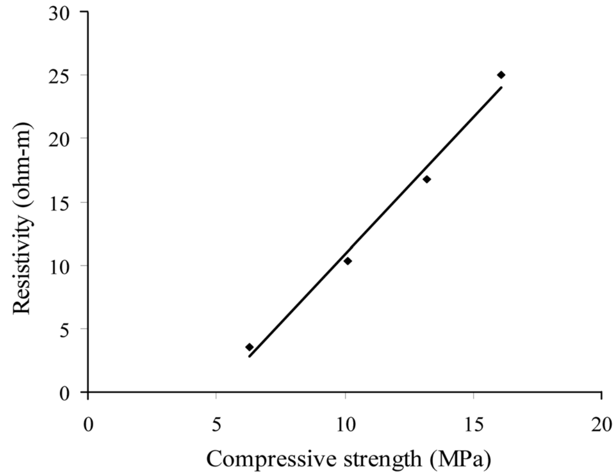

Fig. 6. Relationship between electrical resistivity and compressive strength of mortar made with w/c of 0.65.

formed so that more fine sand particles are bonded together resulting in a denser mortar (Horpibulsuk *et al.*, 2003). The content of free water drops steadily with an increasing hydration age until hydration has completed. This characteristic leads tortuous pathway for the flow of electrical current in the mortar specimens. Thus, the electrical resistivity of the mortar increased with time.

Compressive strength of mortar

The compressive strength for water to cement ratios (0.35 and 0.65) of mortar specimens at the age of 1, 3, 7, 14 and 28 days are presented in Fig. 5. It shows that the compressive strength of the mortar specimens increases with time. The water to cement ratio plays an important role, especially in the compressive strength of mortar. The result, in addition shows that compressive strength of mortar with diverse water to cement ratio is varies. It is due to the fact that 0.35 w/c ratio occupies more cementing material than 0.65 w/c ratio.

The relationship of resistivity with compressive strength

The compressive strength of mortar mainly depends on the microstructural development that is also related to an increase of mortar resistivity. It could be considered that there would be a relationship between the electrical resistivity and the compressive strength. The relationship between the compressive strength of mortar with water to cement ratio of 0.65 and its resistivity is shown in Fig. 6. There is a linear relationship exists between resistivity and compressive strength, that is, a high resistivity corresponds to a higher compressive strength. An empirical equation is derived from Fig. 6:

$$q_u = 2.1679\rho - 10.86, \quad (6)$$

where, q_u = compressive strength and ρ = electrical resistivity

Practical Application

The correlation between electrical resistivity and compressive strength for w/c 0.65 has been shown in equation 6. This correlation is a good starting point for the application of a resistivity method for strength measurement on site but, for each change of the w/c ratio, a new correlation line has to be determined. It is expected that these new correlations between electrical resistivity and compressive strength can be used for checking and controlling the quality of grouted zone.

Conclusions

The electrical resistivity and the compressive strength of the mortar were assessed. The ultimate goal was to evaluate the influence of critical factors that affect electrical measurements and compressive strength in mortar. Water to cement ratio is observed as the primarily mix design parameter affecting the mortar resistivity and compressive strength. The mortar resistivity for a w/c of 0.35 is much higher than that of 0.65. The result showed that the resistivity of mortar decreases markedly with the increase of w/c and that the resistivity of mortar is strongly dependent on the state of the moisture content. With the increase of moisture content beyond 60 % saturation, the resistivity value of mortar drops abruptly. Furthermore, the resistivity of mortar increases with age, in a very similar way to compressive strength. The laboratory test results showed that the electrical resistivity of the mortar prepared in the laboratory has a reasonable good correlation with the compressive strength. Therefore, it is expected that this method can be used to qualitatively evaluate the grouted zone. Moreover, this method is a nondestructive as well as time effective.

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References

Archie, G. E., 1942, The electrical resistivity log as an aid in determining some reservoir characteristics, *Transitions of the AIMME*, **146**, 54-62.

Browne, R. D., 1982, Design prediction of the life for reinforced concrete in marine and other chloride environments, *Durability of Building Materials*, **1**(2), 113-125.

Christensen, B. J., Coverdale, R. T., Olson, R. A., Ford, S. J., Garboczi, E. J., Jennings, H. M., and Mason, T. O., 2005, Impedance spectroscopy of hydrating cement-based materials: measurement, interpretation, and application, *Journal of the American Ceramic Society*, **77**(11), 2789-2804.

Elsener, B., 1988, Electrochemical methods for evaluating reinforced concrete structures, SIA Documentation D020, Non-destructive test of reinforced concrete structures, Swiss Association for Engineers and Architects, Ziirich, 27-37.

Fazeli, M. A., 2007, Construction of grout curtain in Karstic environment case study: Salam Farsi Dam, *Environmental Geology*, **51**(5), 791-796.

Fu, X. and Chung, D. D. L., 1998, Sensitivity of the bond strength to the structure of the interface between reinforcement and cement, and the variability of this structure, *Cement and Concrete Research*, **28**(6), 787-793.

Gowers, K. R. and Millard, S. G., 1999, Measurement of concrete resistivity for assessment of corrosion severity of steel using Wenner technique, *ACI Materials Journal*, **96**(5), 536-541.

Horpibulsuk, S., Miura N., and Nagaraj, T. S., 2003, Assessment of strength development in cement admixed high water content clays with Abram's law as a basis, *Geotechnique*. **53**(4), 439-444.

McCarter, W. J., 1996, Assessing the protective qualities of treated and untreated concrete surfaces under cyclic wetting and drying, *Building and Environment*, **31**(6), 551-556.

Michaux, M., Fletcher, P., and Vidick, B., 1989, Evolution at early hydration times of the chemical composition of liquid phase of oil- well cement pastes with and without additives part I: Additive free cement pastes, *Cement and Concrete Research*, **19**(3), 443-456.

Michaux, M., Nelson, E. B., and Vidick, B., 1990, Chemistry and Characterization of Portland Cement, Well Cementing, E.B. Nelson (ed.), *Elsevier Science Publishers*, Amsterdam Chap. 2.

Millard, S. G., 1991, Reinforced concrete resistivity measurement techniques, Proc. Institution Civil Engineers, part 2, 71-88.

Perez-Pena, M., Roy, D. M., and Tamas, F. D., 1989, Influence of chemical composition and inorganic admixtures on the electrical conductivity of hydrating cement pastes, *Journal of Materials Research*, **4**(1), 215-223.

Prentice, G., 1991, *Electrochemical Engineering Principles*, Prentice-Hall, Englewood Cliffs, New Jersey.

Wenner, F., 1916, A method of measuring earth resistivity *U.S. Bureau of standard Bulletin*, **12**, 469-478.