Comparison of various electrode instrumentations for electrical measurement of cement-based materials

Tsung-Chin Hou [1]; **Huang-Hsing Pan** [2]

Summary

Electrical properties of cement-based materials have been investigated for developing materials' self-sensing characteristics in the past few decades. Smart materials, with self-sensing as its primal functionalities can be achieved through the electrical measurements of the materials itself. These electrical measurements are then used to interpret materials' mechanical status, such as strain and damages, without the inclusion of external sensors. Electrical measurements such as resistivity, however, have been revealed highly dependent on the electrode instrumentations of the studied cement-based objects. In this paper, we compared the differences of electrical measurements among various electrode instrumentations commonly used in laboratory and field. In particular, embedded and attached electrode methods are both used on concrete specimens. Point electrodes and plane electrodes, which generate different types of electric fields between adjacent poles, are also investigated. The corresponding results of resistivity and polarization measurements are compared and discussed. A reliable electrode instrumentation approach is suggested for further studies on electrical characterization of cement-based materials.

Keywords

cement-based materials, electrode instrumentation, electrical measurement, resistivity, polarization effect.

Theme

Tests – green structures / sustainability – concrete

1. Introduction

Concrete structures are continuously exposed to various environmental strikes caused by natures, such as corrosions, rainfall, snow, earthquakes, erosions, and freeze-thaw cycles, among many others. In addition to this, human activities such as traffics, vibrations, collisions, and impacts would also deteriorate structures' integrity accompanied by structures' aging. Therefore, it is often required that structural inspection together with maintenance works to be performed regularly, so as to protect users' life and properties from unexpected loses. In recent decades, numerous of structural inspection approaches, particularly non-destructive examination (NDE), have been proposed for health monitoring and damage detection of concrete structures. Acoustic emission [1,2], ultrasonic detection [3] after the occurrence of damages, liquid penetration [4], and dynamic mechanical testing [5] are all attracting massive attentions and progressively developing. Among those, electrical measurement has shown to be efficient and economic a NDE approach for detecting concrete's physical phases such as temperature, stress, strain, curing, and cracking, etc [6].

While electrical measurement has been suggested for non-destructive inspection of concrete structures since 1942 [7], it is also recognized that the acquired electric signals and the resulting determination of structures' integrity would vary with the electrode instrumentations [8]. As of to the date, there are several types of electrode instrumentations proposed for electrical measurement of cement-based materials. Comparing to four-terminal probe method, two-terminal probe method offers a more rapid instrumentation option for practice, while four-terminal probe method gives more consistent an electric signal, particularly when the homogeneity

[1] Assistant Professor, Dpt. of Civil Eng., National Kaohsiung University of Applied Sciences tchou@cc.kuas.edu.tw

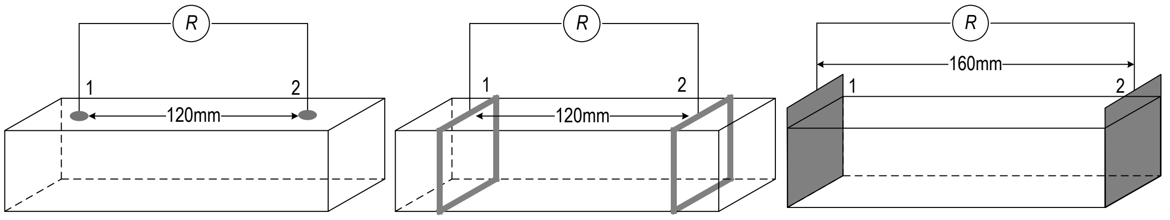
[2] Professor, Dpt. of Civil Eng., National Kaohsiung University of Applied Sciences pam@cc.kuas.edu.tw

of the concrete structures is significantly scattered. Furthermore, unlike surface-contacted electrode with which probes are installed on objects' surfaces or perimeters [9,10], embedded electrode method would provide cement-based materials a more homogeneous electric field for electrical measurement. It causes no significant perturbation to the structural integrity, but does require more sophisticated preparing work. In this paper, we have compared various types of electrode instrumentations for electrical measurement of cement-based materials. Surface-contacted electrode with two-point probe (SC2P), two-surround probe (SC2R), two-plane probe (SC2L), and four-point probe (SC4P) as well as embedded electrode with two-point probe (EB2P), and embedded electrode with four-point probe (EB4P) methods are orderly studied. The physical phases of cement-based materials being investigated include bulk resistivity with respect to material composition and curing age.

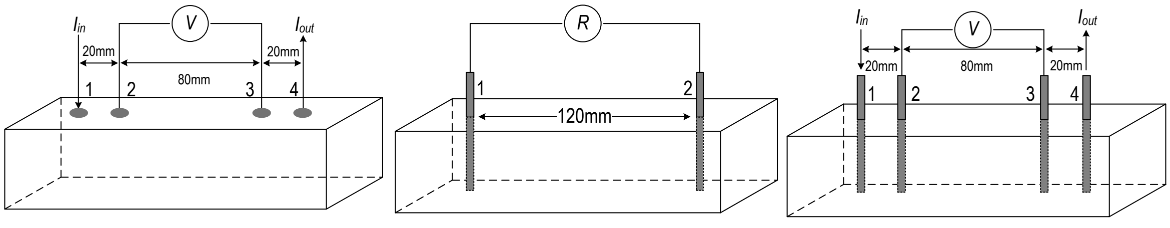
2. Experiments

2.1 Specimen geometry and electrode instrumentations

In this study, specimens are prepared with the dimensions of 40x40x160 mm, which is suggestively representative for material property characterization (in this study, composition, freeze-thaw cycles, and curing age). Material composition of the specimens would be described in later section. The corresponding electrode instrumentations are as shown in Figure 1. For SC2P, simply two round circles prepared by conductive paste with a 120mm spacing are placed on specimens' surface (Figure 1a). Similarly, SC4P has four round circles on specimens' surface with the three spacing of 20mm, 80mm, 20mm, respectively (Figure 1d). SC2R has two surrounded electrodes prepared by copper tape along specimens' perimeters, as shown in Figure 1b. The two plane probes for SC2L are prepared by conductive paste and copper plates that are placed at the two ends of the specimens with a clear electrode spacing of 160mm, as depicted in Figure 1c. It is worth of mentioning that in this study, we polished the specimen end before attaching copper plates onto it so as to ensure an interfacial contact between electrodes and concrete elements. As for EB2P, two copper sticks are embedded into specimens' interior with the electrode spacing of 120mm, as shown in Figure 1e. Similar to SC4P, four electric terminals are placed with the spacing of 20mm, 80mm, 20mm, while the copper stick electrode s are embedded into specimens' interior, as shown in Figure 1f. It should be noted that the embedding depth of the electrode for EB2P and EB4P are 40mm, thoroughly equal to the specimen dimension.



a. SC2P b. SC2R c. SC2L



d. SC4P e. EB2P f. EB4P

Figure 1: the corresponding six types of electrode instrumentations for electrical resistance measurement

2.2 Material composition and resistivity computation

There were four groups of cement-based specimens being studied in this paper, including plain cement (Group 1), 15% weight of fly ash (Group 2), 30% weight of slag (Group 3), and 1% volume of graphite (Group 4) binders. CNS 61 Type I Portland cement, F grade fly ash, and ASTM C989 standard slag were selected and used in the preparation of the specimens, respectively. The particle size of graphite powder is 30nm in diameter, and is supplemented with specified dispersant. Specimens were prepared and cured in sealed bag at room temperature for 1, 7, 14, 21, 28 days before tests. The mixing proportion for all groups is summarized in Table 1. Porous structures of the cement-based specimens were also observed using optical microscope (OM) and will be discussed in later section

Table 1 Mixing proportion by weight (%)

w/b	0.4				
Group #	water	cement	fly ash	slag	graphite
1	40	100	–	–	–
2	40	85	15	–	–
3	40	70	–	30	–
4	40	99 (by volume)	–	–	1 (by volume)

In this study, electrodes for EB2P and EB4P were installed upon the casting work of cement mixtures while the rest types of electrodes were installed after 1 day of curing. As for the electrical measurement, Keithley 2611 System Source Meter was employed for both current supply and voltage measurements. A direct resistance measurement was obtained for all the two-terminal electrode instrumentations, while the resistance of SC4P and EB4P was obtained by dividing the voltage output to the current input. Once the bulk resistance was obtained, resistivity was then computed with respect to the type of electrode instrumentation. For SC4P, equation proposed by Smith [11] for surface-contacted point probes was used:

$$\rho = \frac{2\pi \frac{V}{I}}{\frac{1}{S_1} - \frac{1}{(S_2 + S_3)} - \frac{1}{(S_1 + S_2)} + \frac{1}{S_3}} \tag{1}$$

where S_1 and S_3 are the spacing of the exterior electrode pair and S_2 the interior one. In other words, S_1 = 20mm, S_2 = 80mm, and S_3 = 20mm are the spacing parameters in this study. For SC2P, SC2R, SC2L, and EB2P, a homogeneous current distribution was assumed to be traveling from electrode 1 to electrode 2. This proposition is particularly true for SC2L since the electrode size has covered the entire cross section of the cement-based specimens, as illustrated in Figure 1c, and thus, creates a uniform electric field between electrodes. However, this assumption is less solid in the order SC2R > EB2P > SC2P, determined by the electrode-specimen contact area. Whether or not the true resistivity of the cement-based was obtained, the consistency of electrical measurement is of more concern in this study. Thus, a simple equation for resistivity computation is used here:

$$\rho = R \cdot \frac{A}{L} \tag{2}$$

where *A* is the cross section area of the specimen (40mm X 40mm) for SC2R and SC2L, half the contact-surface of the embedded electrode (0.5 X π X 1mm X 40mm) for EB2P, and the area of the circle electrode for SC2P. *L* is the distance between the electrodes, as shown in Figure 1.

Recently, Hou et al. [12] have proposed an approach for computing the electrical resistivity of cement-based materials instrumented with embedded four-terminal probe:

$$\rho = \Delta V / I \cdot \pi d / \ln((S_1 + S_2)/S_1) \tag{3}$$

where S_1 is the spacing of the exterior electrode pair and S_2 the interior one. In this study, S_1 = 20mm and S_2 = 80mm. It should be mentioned that equation (3) is based on the following assumptions:

1. current moves along the latitude of probe array, as shown in Figure 2
2. current density is evenly distributed along the probe longitude
3. the interior electric field of each probe is neglected
4. potential between the inner electrodes only depends on the resistivity of the conducting medium

a. current paths side view

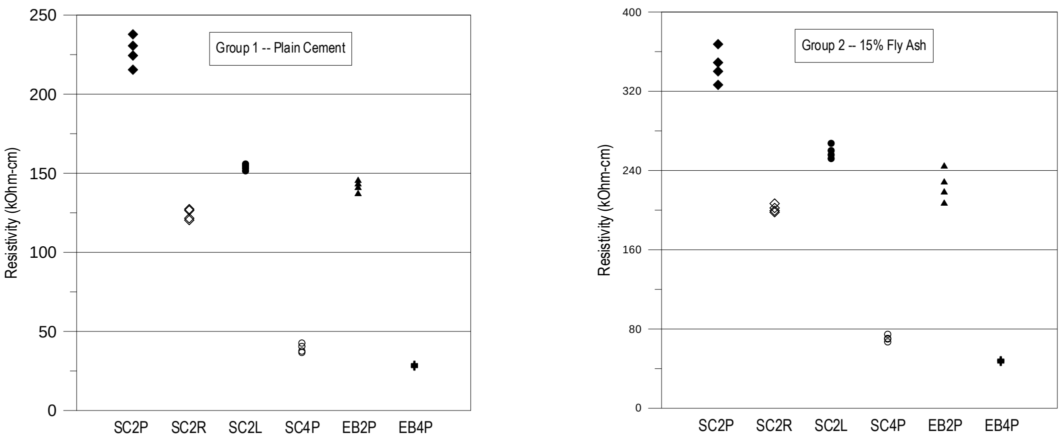
b. current paths top view

Figure 2: current paths of the embedded four-terminal probe [12]

3. Results and discussion

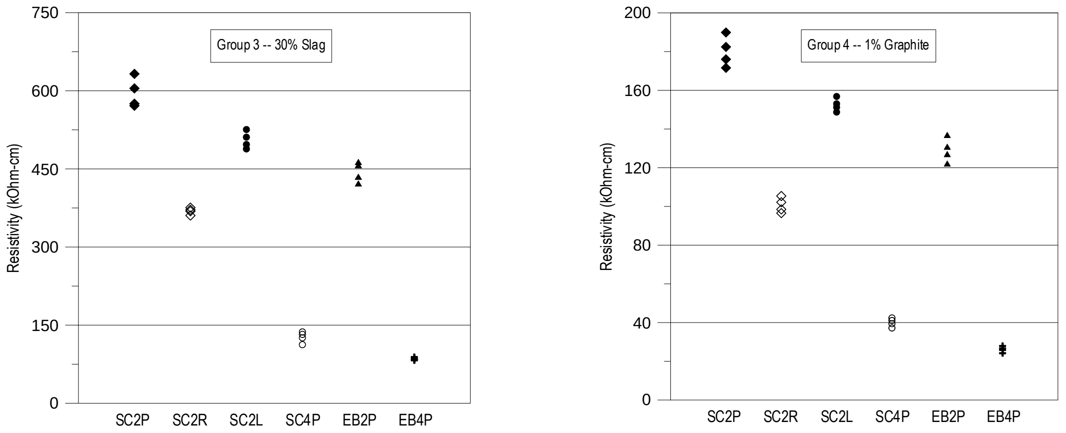
3.1 Material composition – static DC resistivity

The four groups of specimens were cured at room temperature for 21 days before static DC resistivity measurement was performed. Electrical instrumentations of the surface-contacted electrodes were installed onto the specimen six hours before testing, while the embedded ones were installed upon the casting work of cement mixtures. Whichever



a. group 1 – plain cement

b. group 2 – 15% fly ash



c. group 3 – 30% slag

d. group 4 – 1% graphite

Figure 3: comparison of DC resistivity obtained from various types of electrode instrumentations

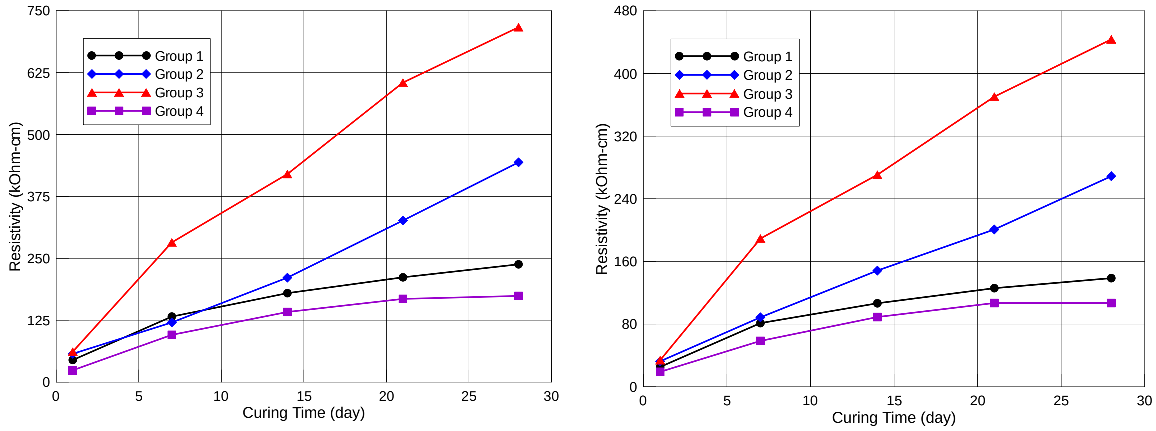
approach is employed, it is expected that post-instrumentation of the electrodes can rapidly be applied to existing concrete structures. Four specimens were tested for each composition with a specified instrumentation type, so as to observe the consistency of the electrical measurement. Figure 3 shows the computed resistivity of all tested specimens. Although the influences of material composition to the absolute resistivity are less of interests in this study, it is still worth of mentioning that material resistivity was significantly enhanced with the inclusion of fly ash and slag. Similarly, the addition of conductive particle (graphite powders) has slightly lowered the material resistivity although the effects are not as significant as expected.

By comparing the DC resistivity obtained from various instrumentation types, it is obviously that four-terminal approaches (SC4P and EB4P) provided better measurement consistency than all the two-terminal methods except for SC2R. For highly resistive conducting medium such as concrete as well as many other cement-based materials, the resistance of the measuring probe can rationally be neglected. However, the uniformity of the interior current paths and the influence of the material-electrode interfaces do cause significant effects to the electrical measurements. An overall higher resistivity of two-terminal than four-terminal approaches could further justify this observation, as it holds true for all the material compositions. In particular, EB4P was shown to offer better measuring consistency than SC4P when the material resistivity was raised by fly ash and slag.

3.2 Curing age – static DC resistivity

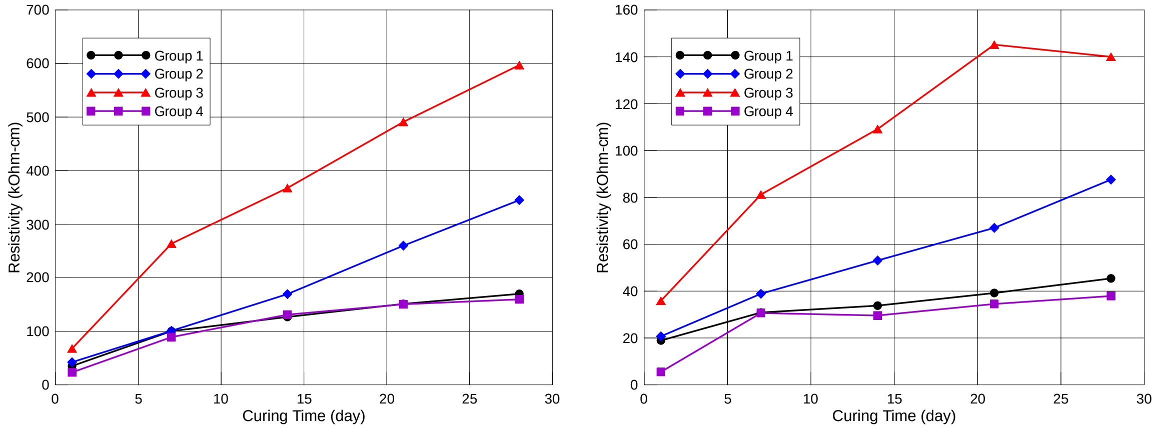
All the four groups of cement-based specimens were instrumented with the six types of electrodes mentioned above for curing age – static DC resistivity test. Electrical measurements were carried at various curing age (1, 7, 14, 21, 28 days) with direct current of 10mA as the input. Similar to material composition test, electrical instrumentations of the surface-contacted electrodes were installed onto the specimen six hours before testing, while the embedded ones were installed upon the casting work of cement mixtures. In this section, the consistency of electrical measurement aims at material curing age rather than on material composition. As a result, only two specimens of each material group with a specified instrumentation type were tested. The mean instead of individual resistivity values were then presented, respectively.

Figure 4 shows the EB4P resistivity measurement with various electrode instrumentations. As expected, resistivity grew with age due to hydration effects of the cement binders, such as reduction of ionic concentration, vaporization of water, formation of porous structures, etc. After 1 day of curing, resistivities of the four groups stand close still, but grew individually with different rates after 7 days. Among those, group 2 and 3 shows relatively larger resistivity values than group 1. Similarly, the 28-day resistivity of group 2 is about 2.1 times the value of group 1. Same results were all well captured by six types of electrode instrumentations, which suggest that although the bulk material resistivity varies with respect to the type of instrumentation, the resistivity growth due to hydration process were not twisted or diluted. These consequences were attributed to the replacement of cement by fly ash and slag, which would reduce the concentration of hydroxyl ions (OH⁻) of the binders and thus, shrink the size of pore distribution [13-14]. The OM images taken at 28 days of curing age (Figure 5(a), (b), and (c)) have further confirmed this.



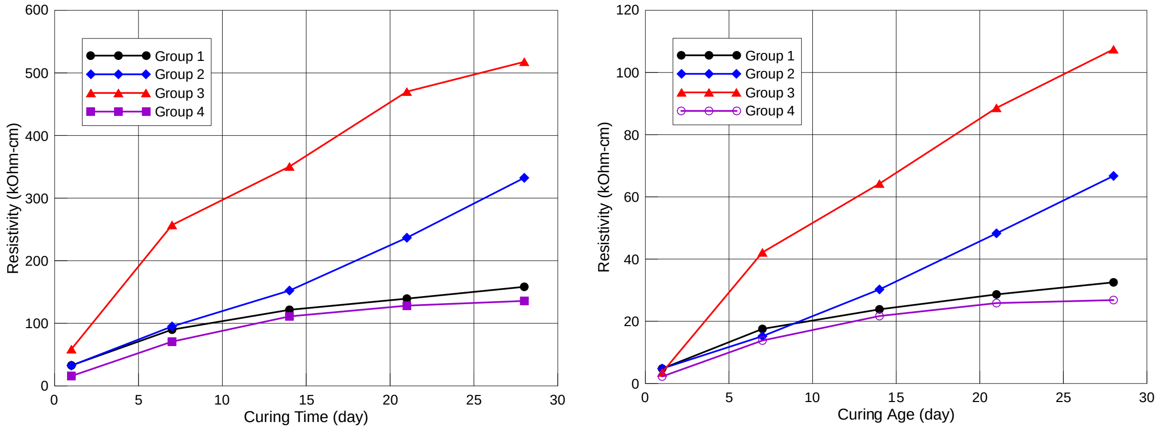
a. SC2P

b. SC2R



c. SC2L

d. SC4P



e. EB2P

f. EB4P

Figure 4: effect of curing age on electrical resistivity

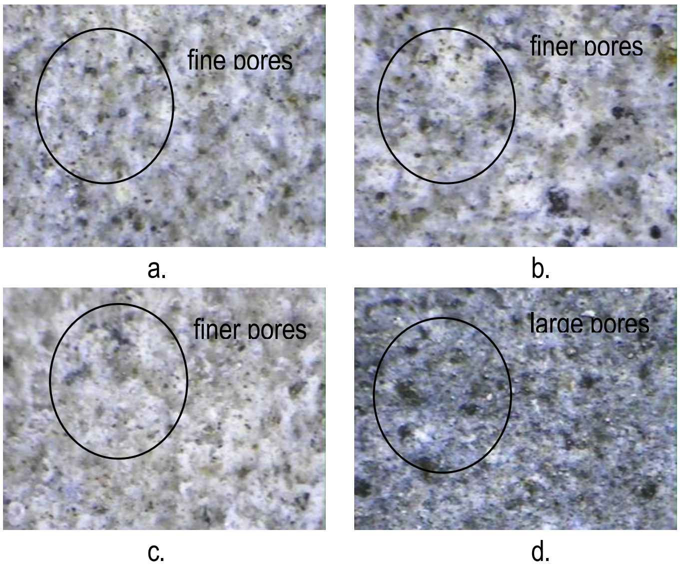


Figure 5: OM images (×300) of (a) plain cement, (b) 15% fly ash, (c) 30% slag, and (d) 1% graphite binders

Conclusions

Based on our investigations on the comparison of various electrode instrumentations for electrical measurement of cement-based materials, the following conclusion can be made:

- four-terminal approaches (SC4P and EB4P) can provide better measurement consistency of resistivity than all the two-terminal methods except for SC2R.
- the uniformity of the interior current paths and the influence of the material-electrode interfaces do cause significant effects to the electrical measurements.
- EB4P was shown to offer better measuring consistency than SC4P when the material resistivity was raised by fly ash and slag.
- replacing cement by certain amount of fly ash and slag would significantly increase the binder resistivity. On the other hand, inclusion of conductive graphite particles would slightly reduce the binder resistivity.
- although the bulk material resistivity varies with respect to the type of instrumentation, the resistivity growth due to hydration process were not twisted or diluted.

Acknowledgments

The authors would like to express their gratitude to the National Science Council (Taiwan) for support of this research. (Grant Number NSC 99-2221-E-151-025)

References

[1] Labuz, J.F., Cattaneo, S. and Chen, L.H., “Acoustic emission at failure in quasi-brittle materials,” Construction and Building Materials, Vol. 15, pp.225-233, 2001.

[2] Shigeishi, M. and Colombo, S., “Acoustic emission to assess and monitor the integrity of bridges,” Construction and Building Materials, Vol. 15, pp.35-49, 2001.

[3] Yeih, W. and Huang R., “Detection of the corrosion damage in reinforced concrete members by ultrasionic testing,” Cement and Concrete Research, Vol.28, No.7, pp.1071-1083, 1998.

[4] Ryall, M.J., Bridge Management – 2nd Edition, Butterworth-Heinemann, pp.141-176, 2010.

[5] Burgueño, R., Karbhari, V.M., Seible, F., and Kolozs, R.T., “Experimental dynamic characterization of an

FRP composite bridge superstructure assembly," Composite Structures, Vol. 54, pp. 427-444, 2001

[6] Wen, S. and Chung, D.D.L., "Damage monitoring of cement paste by electrical resistance measurement," Cement and Concrete Research, Vol. 30, pp.1979-1982, 2000.

[7] Archie, G.E., "The electrical resistivity log as an aid in determining some reservoir characteristics," Transactions of the American Institute of Mining and Metallurgical Engineers, Vol. 146, pp.54-62, 1942.

[8] Millard, S.G. and Gowers, K.R., "The influence of surface layers upon the measurement of concrete resistivity," Proceedings, Second CANMET/ACI International Conference on Durability of Concrete, SP-126, pp.1197-1220, American Concrete Institute, Farmington Hills, MI, 1991.

[9] Gowers, K.R. and Millard, S.G., "Measurement of concrete resistivity for assessment of corrosion severity of steel using Wenner Technique," ACI Materials Journal, Vol. 96, No. 5, pp.536-542, 1999.

[10] Millard, S.G., "Reinforced concrete resistivity measurement techniques," Proceedings, Institute of Civil Engineers, Part 2, pp.71-88, 1991.

[11] Smits, F. M., "Measurement of sheet resistivities with the four-point probe," The Bell System Technical, pp.711-718, 1958.

[12] Hou, T.C., Chiou Y.H., Pan, H.H., and Chang C.H., "Electrical resistivity measurement of cement-based binders using embedded four-terminal probe method," Proceedings of the 4th ACF International Conference, Taipei, Taiwan, 2010.

[13] Ehtesham, S. and Rasheeduzzafar, H., "Corrosion resistance performance of fly ash blended cement concrete," ACI Materials Journal, Vol. 91, No. 3, pp.264-271, 1994.

[14] Hope, B.B. and Ip, A.K., "Corrosion of steel in concrete made with slag cement," ACI Materials Journal, Vol. 84, No.6, pp.525-531, 1987.