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ELECTRICAL RESISTIVITY OF CEMENT TYPES IN REINFORCED CONCRETE STRUCTURES OF ELECTRICALLY POWERED TRANSIT LINES

A. Keyvani

Civil Engineering Department, Faculty of Engineering, Azarbaijan Shahid Madani University, Tabriz, Iran
keyvani@azaruniv.edu

Abstract- Electrical resistivity is an important physical property of concrete that affects a variety of applications. Therefore, any changes in the volume fraction of this matrix will affect the electrical resistivity of concrete. Present research has been underway to demonstrate the electrical resistivity of cement and mix design and effects of performance based specification and proper construction practices in reducing the life cycle cost of reinforced concrete structures especially foundation of power stations, concrete ties and slabs track of electrically power transit lines. Results of this research with DC current showed that age, W/C ratio of specimens, cement types are parameters, which affect resistivity of cement paste and therefore concrete matrix. Specimens with low W/C ratios due to reducing pore water volumes showed decreasing electrical resistivity of matrix. Also increasing age of specimens and decreasing free water volumes in matrix caused very low resistivity, which is an important factor in controlling corrosion, and resistivity.

Keywords: Resistivity, Humidity, Concrete, Cement Paste, DC Current.

I. INTRODUCTION

Electrical resistivity is an important physical property of Portland cement concrete that affects a variety of applications. Electrical resistivity (or its inverse, conductivity) is important as a measure of the ability of concrete to resist the passage of electrical current. This has direct relevance to such applications as Cathodic protection systems and hospital operating room floors, where low resistivity is required and electrically powered rapid transit lines, where high resistivity is needed.

Controlled resistivity materials are used for controlled electrical conduction, static charge dissipation, lightning protection, and electromagnetic interference shielding in electronic, mechanical, structural, chemical applications and electrically powered transit lines. In particular, controlled resistivity ceramics, such as alumina-matrix composites containing electrically conducting particulates filler are used as substrates for handling semiconductor wafers, which require static protection [1].

They are also used in form of charge dissipating coating to improve the break down voltage of high power, high vacuum devices. In addition, controlled resistivity ceramics in the form of tiles are used for antistatic floors [2-5]. Controlled electrical resistivity materials are typically in the form of composite materials with an electrically insulating matrix and electrically conductive discontinuous filler, which can be particulate or fibrous. The higher filler content, lower resistivity of composite. These composites include those with polymer, ceramic and cement matrices [1-5, 6-9]. Among all these matrices, cement is the least expensive. In addition, the fabrication of cement matrix composites is inexpensive and takes place at room temperature.

Stray current induced corrosion damage has been associated with world countries DC rail transit systems for more than a century. In European countries, Japan, America, Australia, and Iran there are more than 100 transit authorities operating electrified rail systems in major urban centers. Stray current corrosion problems continue to affect several cities where the transit systems are typically installed in high-density urban areas. Obviously, such urban areas are associated with underground cables and piping (water, gas) systems that can be highly susceptible to this form of corrosion damage.

Transportation agencies across the world due to corrosion or leakage current originating from man-made DC systems, which intentionally or unintentionally use the earth as part of the return circuit (stray currents), invest billions of dollars in reinforced concrete structures as a repair, replacement, and rehabilitation. These projects not only consume resources, but cause significant delays for the motoring public on electrical trains, subways and electrically powered transit lines. The important variables influencing these structures in design and controlled during construction to optimize the life of infrastructure must be considered. The purpose of this study is to identify concrete resistivity and multiple design solutions that result in long life durable reinforced concrete structures in electrical fields.

II. IMPORTANCE OF RESEARCH

In modern system designs, stray current problems are ameliorated with two fundamental measures: (a) Decreasing the electrical resistance of the rail return circuit and (b) Increasing the electrical resistance between the rails and ground. The first measure makes current return through the ground less likely. Steps taken in this direction include the use of heavier rail sections, continuously welded rails, improved rail bonding, and reduced spacing between substations. It is desirable to combine substations with passenger stations. At passenger stations, current flow is highest due to acceleration of trains.

This combination ensures that these peak currents have a very short return path. The rail to soil resistance can be increased by using insulators placed between the rails and concrete or wooden ties and by using insulated rail fasteners. Stray current concerns are particularly relevant when older rail systems are integrated with newer designs. The higher current demand of the modern, high-speed vehicles poses increased stray current risks in the older sections [10, 11]. The overarching principle in this research and implementation program is to extend the life of reinforced concrete structures of power stations or substations, which supply DC current of traction currents by designing and constructing long life concrete structures in such an electrical fields.

In Iran and developed countries, average life of most reinforced concrete (RC) structures has been between 25 to 30 years, after which time RC is typically removed or replaced. Because of low cost of replacing at this time, often replacing the RC structures is preferred. Extending the life of RC structures to 75-100 years is both economical and technically feasible through a fundamental change in the state of practice of design and construction. The designs of new RC structures must include a significant effort in durability related provisions. The constructors and inspectors must then execute these provisions through greater attention to quality [12, 13].

Reinforced concrete used for RC structures either in power stations, bridges and other transportation facilities experience loss of integrity over time caused by poor initial quality, action of de-icing salts, temperature changes, fatigue and, above all, delamination caused by corrosion of reinforcement bars. Electrical resistivity is sensitive to those losses of integrity. In the case of rebar's, differences occur if they are corroded or not and if cracking or delamination is taking place, resistivity anisotropy is also indicative of rebar distribution and concrete integrity [14, 15]. The theory and the basic principles of the resistivity method can be found in reference text books, however, at the different mix design of concrete and curing conditions the cement paste resistivity as one of the main factors in concrete behavior and durability needs to be study [16, 17].

Electrical resistivity of concrete decreases almost linearly with increasing water/cement ratio for given cement content and therefore resistivity can be diagnostic of the compressive strength. Electric current is conducted through moist concrete by ions [18]. The electrical resistivity of concrete is related to microstructure of the cement matrix, its pore structure, porosity, and pore size distribution. Cement chemistry, cement content, Water/Cement ratio (W/C) and use of admixtures are factors which influence the microstructure of cement matrix of concrete as well as the chemistry of the pore solution and therefore influence its electrical resistivity.

Cement content used in the concrete determines the volume of cement paste, and changes in the cement content will have an influence on the electrical resistivity of concrete. Laboratory testing has been completed to assess the voltages and resistivity characteristics for different cement mixtures with time function. The instrumentation plan and the results of the detailed resistivity testing of 2 Portland cements types and with 3 mix design of W/C ratios under DC currents are presented.

III. EXPERIMENTAL PROGRAM AND RESULTS

Research studies were carried out with two types of Portland cements and three types of W/C ratios of 0.25, 0.30, and 0.35. There are five types of Portland cements with variations of the first three according to ASTM C150. Type II gives of less heat during hydration. This type of cement costs about the same as type I. Its typical compound composition is 51% (C_3S), 24% (C_2S), 6% (C_3A), 11% (C_4AF), 2.9% MgO, 2.5% (SO_3), 0.8% Ignition loss, and 1.0% free CaO. A limitation on the composition is that the (C_3A) shall not exceed 8 percent, which reduces its vulnerability to sulfates.

This type is for general construction that is exposed to moderate sulfate attack and is meant for use when concrete is in contact with soils and ground water especially in the areas due to the high sulfur content of the soil. Type V is used where sulfate resistance is important. Its typical compound composition is 38% (C_3S), 43% (C_2S), 4% (C_3A), 9% (C_4AF), 1.9% MgO, 1.8% (SO_3), 0.9% Ignition loss, and 0.8% free CaO. This cement has a very low (C_3A) composition, which accounts for its high sulfate resistance. The maximum content of (C_3A) allowed is 5 percent for type V Portland cement. Another limitation is that the (C_4AF) + 2(C_3A) composition cannot exceed 20 percent.

This type is used in concrete that is to be exposed to alkali soil and ground water sulfates which react with (C_3A) causing disruptive expansion. Measuring electrical resistivity of cement pastes based on different parameters were carried out with the bars shape of 180×40×40 mm that included four probes for measuring specimens current (amperes) and voltages, Figures 1 and 2. The four-probe method currently is the most widely used technique for the field measurement of concrete resistivity. This method originally was developed by Wenner in 1916 to measure earth resistivity. As shown in the Figure 1 four electrodes are equally spaced and a small alternating current is applied between the out electrodes while potential is then measured between the inner electrodes [19].

The resistivity is then calculated using the following equation:

$$\rho = \frac{2\pi dV}{I} \tag{1}$$

where, ρ is resistivity (ohm.cm), d is distance between inner electrodes (cm), V is voltage between probes P_1, P_2 (volts), I is current between probes C_1, C_2 (amperes).

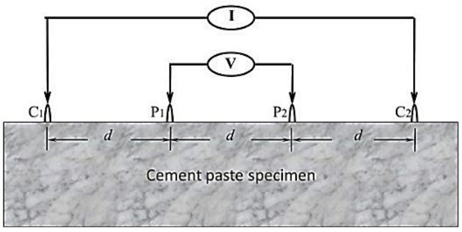

Figure 1. Resistivity test model based on Wenner method

Electrical resistivity of cement pasts at a section of 16 cm^2 of the cement specimens in the defined and equal distances in different ages were measured which are discussed later. Concrete resistivity is the resistance of concrete to the passage of corrosion induced electrical currents. In the propagation phase of the corrosion process a macro-cell is created with the concrete acting as part of the electrical circuit between anode and cathode. By increasing the resistivity of the concrete corrosion will be slowed but not totally stopped.

Figure 2. Cement paste bars for resistivity test setup

Water cement ratio is one of the most important parameters controlling the performance of concrete. It has a significant effect on strength and durability characteristics of concrete. The water cement ratio plays an important role in shaping the microstructure of cement paste and the ionic concentration of its pore solution. Because of these effects, the electrical resistivity of concrete is influenced by the water cement ratio. The results showed the relationship between water cement ratio decreases and resistivity in cement paste. Resistivity of cement paste having water cement ratio of 0.25 was about twice of paste having a water cement ratio 0.35.

Figures 3 to 7 shows the trend of resistivity decrease as water cement ratio increases for different ages of cement specimens. It should be mentioned that resistivity of paste is much lower than that concrete made of the same paste. It can be close to 20% of the companion concrete resistivity in some cases. According to the tests results, Portland cement type 5 in comprising with Portland cement type 2 showed high early resistivity. It means, for sites and environments with high risk of sulfate attach which is needed to use Portland cement type 5, high resistivity also will be obtained but in a longer time. The study of saturation effects in cements with different types showed that during 24 hours of saturation, resistivity of cement type 2 becomes about 2 times of cement type 5 with W/C ratio of 0.25.

However, for W/C ratio of 0.35 and 0.35 the results only showed about 10% increasing. After 2 days and during 6 days of saturation of specimens in water, resistivity for W/C ratio of 0.25 became equal in two types of cements. Also for W/C ratios of 0.30 and 0.35 resistivity in cement type 2 became 1.2 & 1.5 times of specimens with cement type 5, respectively, Figures 3 and 4.

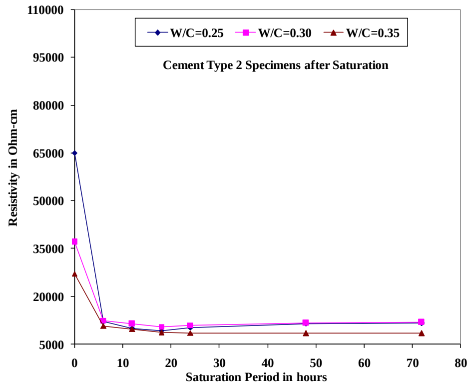

Figure 3. Saturation and resistivity with different W/C ratios for Portland cement type 2

Results of test showed specimens with low W/C ratios reach high resistivity in a short age. However, specimens with high W/C ratio reach high resistivity in a longer time. On other hand, specimen of cement paste bar specimen with 0.25 of W/C ratio reached very high resistivity of 100000 Ohm/cm (physically indefinite) in two days but specimen W/C ratio of 0.35 reached at 15 days, Figures 4 to 7. This phenomenon seems due to additional pore water amount in cement matrix, which facilitates current passage and therefore low resistivity,

when $\rho \geq 120$ Ω-m	corrosion is unlikely
when $\rho = 80$ to 120 Ω-m	corrosion is possible
when $\rho \leq 80$ Ω-m	corrosion is fairly certain.

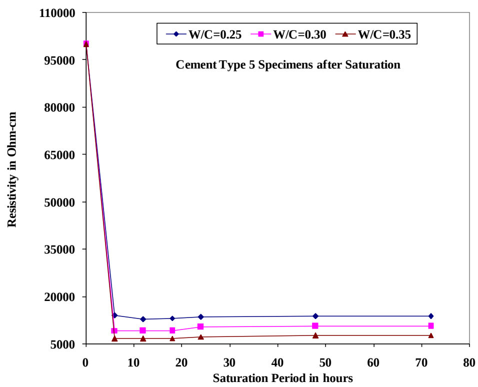

Figure 4. Saturation and resistivity with different W/C ratios for Portland cement type 5

Compressive strength of concrete is dependent on the W/C ratio. The higher the ratio the lower is the strength. Electrical resistivity of concrete decreases almost linearly with increasing W/C ratio for a given cement content and therefore resistivity can be diagnostic of the compressive strength [11]. Electric current is conducted through moist concrete by ions (electrolytic mechanism).

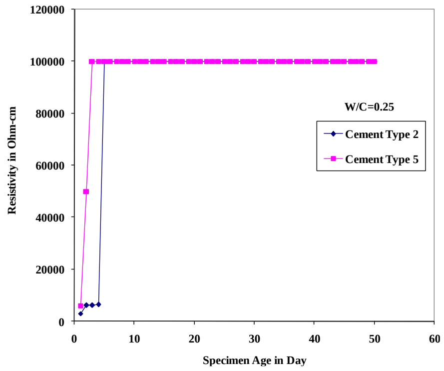

Figure 5. Variations of resistivity in 2 Portland cements types with W/C = 0.25

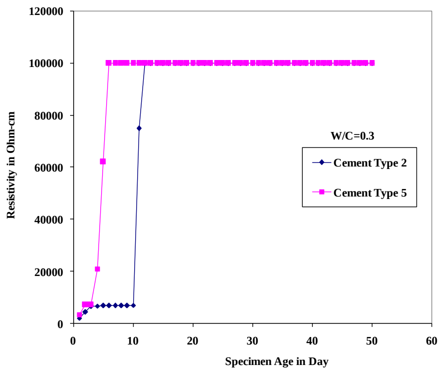

Figure 6. Variations of resistivity in 2 Portland cements types with W/C = 0.30

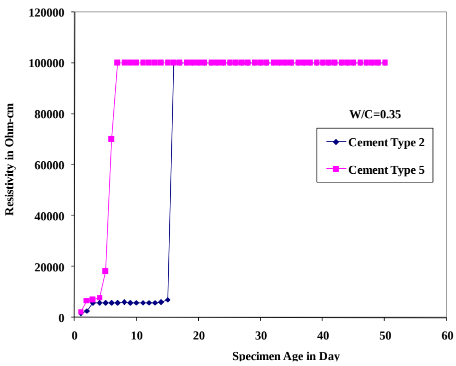

Figure 7. Variations of resistivity in 2 Portland cements types with W/C = 0.35

Figure 8 and 9 shows the resistivity response with curing time for three concrete slabs. Slabs B30-05 and B30-10 display an observed compressive strength of 24.3 MPa for a concrete mixture of 160 lit/m^3 water, 350 kg/m^3 cement (W/C ratio 0.46), 1060 kg/m^3 20 mm aggregates and 830 kg/m^3 sand and air content of 8%. Slab B15-10 displays an observed compressive strength of 9.2 MPa for a mixture of 160 lit/m^3 water, 200 kg/m^3 cement (ratio 0.80) and 950 kg/m^3 sand. Air volume ratio and amount of aggregates are the same as the previous slabs [20]. Progress of corrosion of steel reinforcement is controlled by the electrical resistivity of concrete and therefore it is better to maintain high resistivity within the concrete. Addition of chloride ions originating from deicing salts for example will decrease electrical resistivity and accelerate the generation of corrosion.

Experiments have shown electrical resistivity of concrete is dependent upon its integrity. Presence of water or not in the cracks will modify the bulk resistivity of the material. Therefore, loss of integrity, chloride ions, and compressive strength will affect resistivity of concrete and a method based on mapping of resistivity distribution will help diagnose defects in concrete structures. Corrosion is the spontaneous degradation that a metal undergoes when exposed to an environment, such as air, water, or soil. Corrosion is caused by an electrochemical reaction that takes place between the metal and the environment. There are six forms of corrosion, but only two forms are most often encountered on electrified transit systems, namely, pitting and general corrosion. Corrosion can be localized, taking the form of pits in the surface, or it can be more generalized, forming large areas of metal wastage [21].

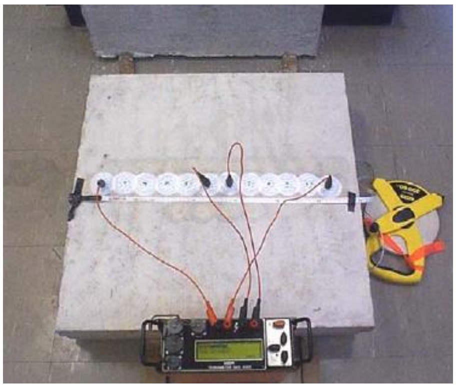

Figure 8. Resistivity measurements on concrete slabs [11]

When corrosion is an electro-chemical process therefore he rate of flow of the ions between the anode and cathode areas, and therefore the rate at which corrosion can occur, is affected by the resistivity of the concrete. To measure the electrical resistivity of the concrete a current is applied to the two outer probes and the potential difference is measured between the two inner probes. Empirical tests have arrived at the following threshold values, which can be used to determine the likelihood of corrosion.

These values have to be used cautiously as there is strong evidence that chloride diffusion and surface electrical resistivity is dependent on other factors such as mix composition and age [22]. The electrical resistivity of the concrete decreases due to:

- Increasing concrete water content
- Increasing concrete porosity
- Increasing temperature
- Increasing chloride content
- Decreasing carbonation depth

When the electrical resistivity of the concrete is low, the rate of corrosion increases. When the electrical resistivity is high, e.g. in case of dry and carbonated concrete, the rate of corrosion decreases.

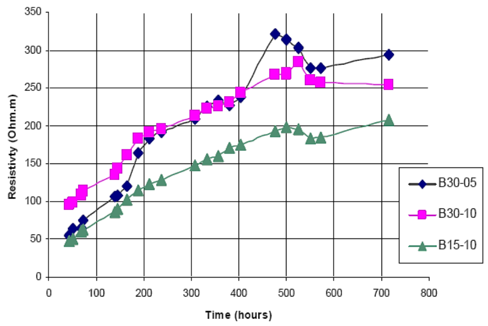

Figure 9. Resistivity as function of curing time for three concrete slabs, the Wenner spread is used [20]

IV. CONCLUSIONS

Electrical resistivity is an important consideration in such applications as cathodic protection systems and hospital operating room floors, where low resistivity's are required and electrically powered rapid transit lines, where high resistivity's are needed. Low cost controlled electrical resistivity materials based on Portland cement is also important where reinforced concrete will be exposed to corrosive conditions, as corrosion currents will flow more easily in concrete having low resistivity.

Compressive strength of concrete is dependent on the W/C ratio. The higher the ratio the lower is the strength. Electrical resistivity of concrete decreases almost linearly with increasing W/C ratio for a given cement content and therefore resistivity can be diagnostic of the compressive strength. Investigation of resistivity in two types of cements based on the ages of specimens showed that specimens with low W/C ratio obtains high resistivity in a short period, however, high W/C ratio of specimens obtain in a longer ages. This phenomenon seems due to additional pore water amount in cement matrix, which facilitates current passage and therefore low resistivity.

Cement type 5 comparing with cement type 2 with W/C ratios of 0.25, 0.30, and 0.35 showed an early and higher resistivity in same conditions. Therefore, for environments of corrosion risk and necessity of high resistivity, applying cement type 5 is strongly recommended. Decreasing saturated conditions of concrete structures will affect resistivity and decreasing its magnitude. In addition, drainage system under structures to lower water access will be useful method to avoid saturation potential and decreasing resistivity risk.

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BIOGRAPHY

Abdullah Keyvani was born in Iran, 1959. He received the B.Sc. and M.Sc. degrees from Iran University of Science and Technology, Tehran, Iran and University of Tabriz, Tabriz, Iran and the Ph.D. degree from University of Hokkaido, Japan, all in Civil Engineering, in 1984, 1987, and 1998, respectively. Currently, he is an Assistant Professor of Civil Engineering Department at Azarbaijan Shahid Madani University, Tabriz, Iran. He teaches advanced concrete structures, design of concrete structures, and concrete technology and laboratory. He is also a Senior Consultant Engineer of the East Azarbaijan Regional Water Corporation, Tabriz, Iran. His research interests are in the area of design, construction, and quality control of reinforced concrete hydro structures.