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Overview of Concrete Durability Evaluation using Electrical Resistivity

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Abstract. The current quality control procedures for concrete production focus mainly on concrete compressive strength. Despite of its relevance to concrete performance, compressive strength testing is poorly correlated to the long term performance of concrete mixes, including the concrete ability to withstand chloride and sulfate attacks, and the concrete capability of protecting the steel bars and prestress strands against corrosion.

This research presents an overview to the use of electrical resistivity testing technique as an alternative quality control procedure that is currently used in assessment of concrete long-term performance. Electrical resistivity testing conducted through surface resistivity (SR) and bulk resistivity depends on measuring the concrete porosity and pores connectivity within hardened concrete samples. The final resistivity measured in ohm-meter is inversly proportional to the pores ratio and pores connectivity. Thus, a higher resistivity is a good indicator to minimal and disconnected pores formation within the concrete, which leads to a better future performance of hardened concrete structural elements. The outcome of electrical resistivity is currently used by several state departments of transportation (DoTs) to improve concrete mix designs, and minimize the potential need to maintenace activities during concrete projects life span.

Keywords: Durability, Resistivity, Conductivity, Corrosion, Chloride Diffusion

1 Introduction

The current quality control procedures for concrete production focus mainly on concrete compressive strength. Currently, different codes and specifications consider the compressive strength of concrete as the main indictor to concrete quality. Different concrete characteristics as modulus of elasticity (MOE) and modulus of rupture (MOR) are calculated by empirical equations as a function of concrete compressive strength.

Despite of its relevance to concrete performance, compressive strength testing is poorly correlated to the long-term performance of concrete mixes, including the concrete ability to withstand chloride and sulfate attacks, service cracking, freeze and thaw cycles, and the concrete capability of protecting embedded steel bars and prestress strands against corrosion. Currently, different research programs consider different testing techniques to assess long-term performance of concrete mixes. These programs focus on measuring the pore percentage within hardened concrete, and the degree of pore connectivity. Larger pore percentage and sufficient connectivity are directly correlated to potential chloride ion infiltration, which accelerates the deteriortion of the concrete section and expedite the corrosion of steel reinforcement. Current specifications permit the use of rapid chloride permeability testing (RCPT) in measuring the resistance of concrete to chloride ingress. The RCPT method [1] uses a 4 in. diameter core or cylindrical sample from the concrete being tested. The cylinder length is 2 in. and is treated according to AASHTO T277 [2] or ASTM C1202 [3]. The sample is exposed to a 60-volt potential for 6 hours, with readings taken every 30 minutes. The amount of coulombs passing through the sample are calculated and correlated to chloride permeability according to specifications. RCPT technique is shown in figure 1.

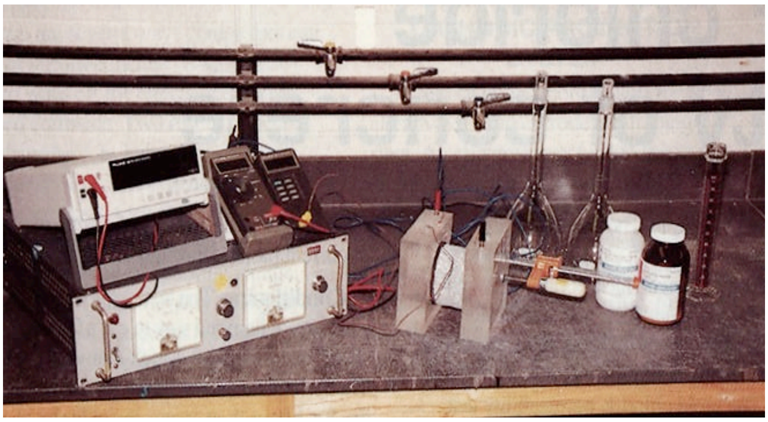

Figure 1: RCPT technique used for concrete durability

While the RCPT test is widely accepted in construction projects within the United States, it is a time-consuming test, laborious, and expensive to conduct. To-date, different research projects are being conducted to evaluate the potential of using bulk and surface resistivity of concrete specimens in replacement of RCPT method. Bulk and surface resistivity techniques are simple, easy-to-perform, and doesn't include complicated testing procedure. The investigation of electrical resistivity measurement is currently conducted to assess the potential use of electrical resistivity for the performance-based evaluation of mix designs, and to optimize standard mixes to attain a predetermined future performance by correlating the measured resistivity to the chloride diffusion co-efficient of concrete [4]

2 Electrical Resistivity Measurements

Two different resistivity techniques are currently used in concrete durability evaluation, namely surface resistivity and bulk resistivity. The two electrical resistivity techniques depend on simple measurement of a given size concrete specimen, using Ohm's law, to determine the electrical resistivity of concrete. The electrical resistivity measurements can be used to assess the quality of concrete, percentage of air voids, void distribution, and existence of good or poor conductive ingredients within the mix as steel fibers for good conductivity, and supplementary cementitious materials which block the air voids within the concrete mix, hence, reduce the electrical conductivity.

2.1 Surface Resistivity

The surface resistivity method as non-destructive testing was initially introduced by geologists to investigate the soil strata (Wenner technique). The surface resistivity method was considered by material engineers as a technique that could be successfully used in measuring the ability of hardened concrete to resist chloride ion penetration according to AASHTO T358-17 [5]. There are three advantages associated with the implementation of the surface resistivity method in long-term performance assessment of concrete: First, surface resistivity is a non-destructive testing method and could be performed on concrete cylinders poured for compressive strength testing. This results in minimal expenses for testing concrete. Second, the surface resistivity method assesses the quality of surface concrete that covers steel bars or prestress strands. This layer of concrete is the most important layer of the pour as all chloride and different adverse environmental conditions attack the concrete and steel from the outside. Third, surface resistivity technique is simple to perform, doesn’t need special expertise, or complicated/expensive testing equipment. The simplicity of surface resistivity method enables construction personnel to conduct the test anywhere and at any time regardless to the nature of the project, including high security buildings and nuclear power plants as no core are required to drill.

The Wenner method in surface resistivity measures depends on four electrodes situated in a straight line at equal distance (a). The two outer electrodes apply an alternate current (AC) with a predetermined frequency and the two inner electrodes measure the potential difference (V). The location of the four probes has to be accurately identified, and there should be a direct contact between the electrodes and the concrete specimen surface. The presence of any aggregates near the sample surface may result in misleading resistivity measurements. The Werner surface resistivity measurement device is shown in figure (2)

Figure 2: Wenner device for surface resistivity measurement

The electrical resistivity is measured using the afore-mentioned device, and the schematic representation of the electric current flow lines, equipotential line, and electrodes positioning is illustrated in the schematic drawing shown in figure (3)

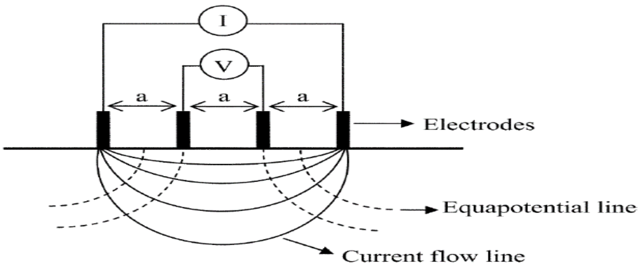

Figure 3: Schematic representation of surface resistivity testing of concrete [6]

The equation for measuring electrical surface resistivity according to Werner technique is shown in equation 1:

$$\rho = 2\pi a(V/I)$$

Equation 1

Where:

V, electrical potential (volts)

I, electrical current (ampere)

A, probe spacing (cm)

2.2 Bulk Resistivity

The bulk resistivity test is conducted according to the standard test method for bulk electrical conductivity of hardened concrete (ASTM C1760-12). The main advantage of bulk resistivity measurement is that the measured resistivity is assessed for the whole concrete sample and not a surface layer only. The bulk resistivity measurement can be conducted as a non-destructive test for concrete cylinders that will be used in measuring the compressive strength of the concrete at any given age. The bulk resistivity test setup is shown in figure 4

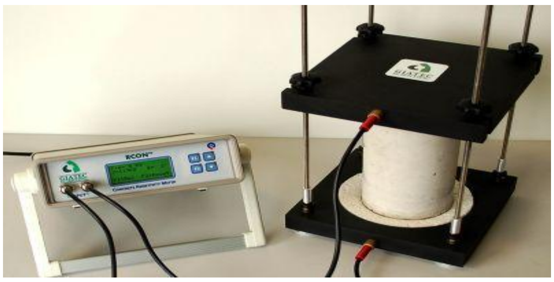

Figure 4: Bulk resistivity measurement device

The effect of the cylinder geometry on the final measurement of concrete resistivity is eliminated by calculating a shape factor (k) for the tested cylinder. The shape factor (k) is calculated as follows:

$$K = A/L$$

Equation 2

Where:

K, shape factor

A, cross section area of the cylinder

L, the height of the cylinder (distance between the probes)

The electrical resistivity of concrete, using bulk resistivity testing technique, is calculated according to the following equation:

$$\rho = K.R \quad \text{Equation 3}$$

Where:

ρ, electrical resistivity of concrete

R, resistance (=V/I of the electric source)

Despite of the advantages associated with the bulk resistivity method, this electrical measurement technique might not be used in given construction projects if it is not possible to access an existing concrete structure from both sides to place the resistivity probes, or drill cores to obtain a sample to be measured in site or in any materials lab.

3 Factors Affecting Electrical Resistivity Measures

Electrical resistivity techniques are currently investigated as an alternative technique to the current RCPT method. Electrical resistivity of concrete is a direct indicator to the hardened concrete quality. Higher concrete resistivity indicates limited pores and lack of pores connectivity. Recent studies showed that the electrical resistivity of concrete is affected by different parameters, as follows:

3.1 Moisture Content of Concrete

The increased moisture content of a concrete specimen results in a higher flow of electrical current within the tested specimen. This is attributed to the higher tendency of water to conduct electricity. Thus, higher water content due to higher water-to-cement ratio in the mix or increased water content of an existing concrete structure due to higher concrete permeability will resist in a lowered resistivity. The lowered resistivity indicates a potential reduced durability.

3.2 Effect of Concrete Cove

The concrete cover is detrimental to the accuracy of electrical resistivity measurement of any concrete sample. Intact concrete cover, with fewer cracks, results in a higher value of concrete resistivity due to the lower flow of moisture through the concrete cover. On the other hand, a low-quality concrete cover, low thickness and/or existence of hair cracks, results in a higher tendency of the concrete sample to permit the passage of electrical charge, which results in a lower concrete resistivity and implies a reduced durability.

3.3 Steel Reinforcement of Concrete

Reinforced concrete structures contain different percentages of steel bars for flexure reinforcement, shear reinforcement, and shrinkage compensation purposes. Bridge girders, and other prefabricated elements, may contain prestressing strands. New generation of concrete mixes with superior characteristics, known as ultra-high-performance concrete (UHPC), contains a higher percentage of steel fibers [7]. The afore-mentioned different types of reinforcement bars results in a higher conductivity of concrete. The lower resistivity calculated due to steel bars embedment shows false measurement of long term durability of concrete. The problems associated with steel reinforcement effect on resistivity reading are non-existent in new construction projects quality control as plain concrete cylindrical specimens are always used.

However, in existing projects, location of steel bars should be determined and avoided prior to the application of resistivity measurement techniques.

3.4 Concrete Temperature

The temperature of concrete specimen is crucial when electrical resistivity is measured. Simply, an elevated temperature allows for faster ionic transfer. So, an elevated temperature of concrete specimen will result in a lower resistivity; and implies a lower performance and reduced durability during the life span of the project.

4 Quality Control of Concrete Mixture

The quality control procedures followed during concrete mix design and production could affect the measured resistivity of concrete mixes. The quality control procedures include: 1) proper mixing, which improves the hydration of the cement paste and minimizes the free moisture which reduces resistivity, 2) curing regimen, which reduces the concrete shrinkage and improves the concrete surface cover [8]

5 Concrete Permeability and Voids Ratio

The percentage of concrete voids is highly dependent on the size and gradation of different granular materials, including coarse aggregates, fine aggregates, Portland cement, and supplementary cementitious materials as fly ash, micro-silica, and nano-silica incorporated in the mix. Recent studies showed that improved gradation of granular particles and resulting low voids ratio results in improved mix resistivity. These results match the findings of other research projects showing that concrete durability could be enhanced using micro and nano-sized supplementary cementitious materials [9, 10]

6 Applications of Electrical Resistivity in Construction Industry

The interpretation of resistivity measurements of concrete and its potential correlation to chloride ion diffusion is currently used in the assessment of instantaneous properties of concrete, and potential long-term performance of concrete construction projects. The following represents a list of applications where electrical resistivity of concrete could be used:

1. *Estimate the concrete voids ratio*: which is an important measure that reflects the potential performance of concrete structures
2. *Detect concrete surface cracks*: which indicates potential risks associated with a concrete structure. Existence of cracks is a potential threat as it enables additional moisture to dissipate into the concrete, and results in corrosion of steel reinforcement.
3. *Ensure overall quality of concrete*: through the overall measurement of resistivity. Higher resistivity is a direct indicator of absence of cracks, lack of free moisture, and a higher packing order of cement and cementitious materials paste. Thus, a higher resistivity could be used as an indicator for performance-based design of concrete mix design and optimization

The use of electrical resistivity in concrete durability evaluation or for performance-based design of concrete mixes has a positive impact on the construction industry in the United States, and on a global level. The successful implementation of electrical resistivity in concrete mix design optimization would result in concrete structures with fewer cracks and better long-term performance, which will increase the life span of construction projects, and minimize the expenditure required for maintenance, repair, and replacement of deteriorated sections. Concrete mix optimization and improved durability results in a lower life-cycle cost of construction projects; and improved national infra-structure.

7 Research Findings

Electrical resistivity measures were successfully used in the assessment of long-term performance of different concrete mix designs based on measuring the resistivity of concrete surface or bulk sample to the passage of electric current. The measured resistivity is affected by the following parameters:

1. Concrete paste design: as higher cement content or the inclusion of supplementary cementitious materials as fly ash, quartz flour, micro silica, nano-silica, and carbon nano-tubes results in improved packing of granular materials, which increase the hardened concrete resistivity. This indicates a better long-term performance of the hardened concrete in the future
2. Chemical admixtures: used in modern projects to attain special properties including early set, delayed set, high workability have a high effect on electrical resistivity of the mix. High chemical dosage results in an increased conductivity of the concrete mix, which reflects a lower long-term performance of hardened concrete

8 Summary and Conclusion

Current projects are shifting to performance-based specifications. According to this recent change, concrete mixes are being optimized by material design engineers, batch plants, and precast facilities to attain predefined short and long-term performance criteria. The main long-term performance criteria specified for concrete mixes is durability. Currently, RCPT is used to assess the long-term performance of hardened concrete by estimating the concrete capability of resisting chloride ingress. Despite of its successful implementation, RCPT has multiple disadvantages as being a time consuming, and laborious technique. Current research projects indicated that concrete electric resistivity can be successfully used in long-term performance assessment of concrete. Two main electrical resistivity techniques are presented to the industry professionals, namely the surface resistivity and bulk resistivity. Electrical resistivity technique correlates the measured concrete resistivity for electric current and the amount of pores and pores connectivity within the hardened concrete surface. Electrical resistivity measurement is affected by different parameters as mix constituents, voids ratio, curing regimen and duration. To-date, several state DoTs implement the electrical resistivity technique in their concrete quality control procedure to attain optimized mix designs with superior long-term performance and minimize future maintenance expenditure.

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