International Journal of Research in Engineering and Science (IJRES)
ISSN (Online): 2320-9364, ISSN (Print): 2320-9356
www.ijres.org Volume 9 Issue 7 ǁ 2021 ǁ PP. 12-19

A Review on Durability Assessment of Concrete Structures Using Electrical Resistivity Method

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Abstract
Degradation processes in reinforced concrete structures that affect durability are partially controlled by transport of aggressive ions through the concrete microstructure. Ions are charged and the ability of concrete to hold out on its electrical resistivity. Hence, a connection could be expected between electrical resistivity of concrete and the deterioration processes such as increase in permeability and corrosion of embedded steel. Through this paper, an extensive literature review has been done to address relationship between concrete electrical resistivity and its certain durability characteristics. These durability characteristics include chloride diffusivity and corrosion of reinforcement as these have major influence on concrete degradation process. Overall, there exists an inverse or direct proportional correlation between these parameters. Evaluated results, from measuring the concrete electrical resistivity, can also be used as a great indicator to identify early age characteristics of fresh concrete and for evaluation of its properties, determination of moisture content, connectivity of the micro pores, and even condition assessment of in-service structures. This paper also reviews and assesses research concerning the parameters such as environmental conditions and presence of steel rebar on measuring electrical resistivity of concrete. Moreover, concrete resistivity concept, application, and its various measurement techniques are introduced.

Keywords: *Electrical resistivity, durability*

Date of Submission: 21-06-2021 Date of acceptance: 06-07-2021

I. INTRODUCTION

The durability of concrete is defined as its ability to resist weathering action, chemical attack, abrasion, or any other deterioration process to retain its original form, quality, and serviceability when exposed to harsh environment. To a large extent, it is commonly accepted that concrete durability is governed by concrete's resistance to the penetration of aggressive media. This media may be present in a liquid or gaseous state and that may be transported by various mechanisms such as permeation, diffusion, absorption, capillary suction, and combinations of the items just mentioned. Hence, for concrete in service, a combined action of various media may prevail and mixed modes of transport processes occur. Moreover, there are correlations between transport parameters of concrete and the following durability characteristics: carbonation, sulphate attack, alkali-aggregate reaction, frost resistance, leaching, soft water attack, acid attack, abrasion, chloride ingress, and reinforcement corrosion.

Consequently, the transport of ions through microstructure of concrete plays an important role in the control of concrete durability. When ions are charged, then it is the concrete's ability to withstand transfer of charged ions which is highly dependent upon its electrical resistivity. In this study, since chloride ingress and reinforcement corrosion are reported as major concrete deterioration processes, one of the main concentration areas is on these durability characteristics and their relationship with concrete electrical resistivity. Over the last few decades, a great deal of attention has been paid to research and development of electrical resistivity measurement techniques as a nondestructive technique (NDT) to evaluate the durability of concrete structures. This method is becoming more popular especially for field evaluations due to its simplicity, rapidness, and cost during test conduction. However, the inclusion of these methods into the standards and guidelines is quite slow.

Electrical resistivity is a material property that can be used for various purposes, one of which is to identify early age characteristics of fresh concrete. When the fresh concrete sets and hardens, depercolation (discontinuity) of the capillary pore space leads to an increase in its electrical resistivity. Since electrical current is conveyed by dissolved charged ions flowing into the concrete pore solution, it is a good indicator of concrete pore structures. This pore structure formation at early-ages can define the long-term durability of concrete. In addition, the tensile strength of cementitious materials at early-ages is low and the material is prone to cracking. This initial cracking also serves as a pathway for deleterious materials to ingress into the matrix. This cracking can also be captured by resistivity measurements and thus helps predict the long-term durability of concrete. In addition, electrical resistivity can be used as an index to determine the moisture content and the connectivity of the micro pores in the concrete. Several researchers attempted to characterize the effects of various parameters on electrical resistivity measurements. One of the important factors affecting the measurements is environmental conditions such as temperature, rainfall, and relative humidity.

During testing, good electrical connection between concrete and electrodes as well as specimen geometry plays a key role in having are liable measurement. The electrical resistivity measurements are highly influenced by the moisture content of concrete. For instance, when the moisture content is reduced, the resistivity is increased significantly. Therefore, considering all these influencing parameters for on-site resistivity measurements and to make meaningful conclusions is not a simple task.

In this paper, the correlation between electrical resistivity and certain durability characteristics of concrete is discussed. These concrete characteristics include chloride permeability, corrosion rate, and compressive strength. Also, different approaches in the measurement of concrete resistivity including bulk and surface resistivity measurements are presented. This paper reviews the effect of several influencing parameters such as external environment (e.g., temperature) and concrete mixture on the electrical resistivity.

II. DURABILITY ASSESSMENT AND INFLUENCING FACTORS OF ELECTRICAL RESISTIVITY

Young-Chul Lim (2010), [13] This study proposes a new method for the nondestructive testing of deterioration caused by corrosion in concrete structures by estimating the surface resistivity of steel. For this purpose, the resistivity on the surface of a steel bar is assumed to behave similarly to the polarization resistance with the progress of corrosion. The resistivity of the steel surface is estimated using the resistivity estimation model (REM), and it is used as an index of the corrosion state. The REM is a mathematical model that considers geometric factors influencing the measurement, such as the cover depth, reinforcement radius, and electrode interval, and it can be used to estimate the resistivities of the concrete and steel bar in concrete structures. In addition, the possibility of applying this resistivity estimation method is investigated by performing an experiment on the accelerated corrosion of steel. In this study, a resistivity estimation method that employs both the technique of the resistivity method and the concept of the steel surface resistivity was proposed for the quantitative evaluation of the corrosion of reinforcement as a completely nondestructive measurement approach for concrete structures. The results of this study are as follows. The steel surface resistivity for corrosion can be found in the low-frequency range from the large effect of the boundary surface between concrete and steel. The electrode interval must be decided according to the geometric conditions of the reinforcing bar. In particular, since the steel resistivity must be estimated from the response voltage in the low-frequency region, the electrode interval must be sufficient to include the boundary surface between concrete and steel. The steel resistivity estimated from the apparent resistivity clearly decreased with the progress of corrosion.

Miroslav Brodoan (2017), [5] The determination of reinforcement corrosion using the electrical resistance method of embedded bars in the concrete beams in laboratory conditions is described in this paper. For comparison, the achieved data from non-destructive measurements were compared to data from subsequent destructive tests when weight losses were recorded for each of the steel bars after their exposure time. Laboratory measurements of the reinforcements were realized particularly for verification of whether the electrical resistance method could be suitable for an in-situ corrosion-evaluation process. The next part of the research was focused on the corrosion simulation of the steel reinforcement in reinforced concrete. The effect of corrosion was simulated by a nonlinear numerical analysis with the program ATENA 3D using corrosion-rate data from a laboratory test.

A great advantage of these methods is the fact that in the case when the reinforcements with known entrance electrical resistance are inserted into the structural element, we can relatively easily and inexpensively determine the status of other reinforcements, without the destructive interference with the concrete cover layer. From the obtained results this monitoring method is useful for the quantity corrosion reinforcement evaluation. The determination of the actual state of steel bars is a major criterion in the decision-making process for consequent reinforced-concrete structures redevelopment.

Romain Rodrigues (2020), [1] this study provides an up-to-date review on corrosion mechanisms and recent advances in electrical methods for corrosion monitoring. When assessing corrosion mechanism, the inherent heterogeneity of RC structures and the significant effect of environmental factors remain major issues in data interpretations. The steel surface condition and local in homogeneities at the steel–concrete interface appear to have an important effect on corrosion initiation. Considering uniform corrosion in atmospherically exposed RC structures, the two main influencing factors of the corrosion process are the water content and the pore structure at the steel–concrete interface. However, irrespective of the depassivation mechanism, i.e. carbonation or chloride-induced corrosion, non-uniform corrosion is expected to be the main process for RC structures due to local variations in environmental exposure or the presence of interconnected rebars with different properties. Concerning corrosion monitoring using electrical methods, the half-cell potential technique with potential mapping is accurate for locating areas with a high corrosion risk. The use of electrical resistivity tomography allows to consider appropriately the inherent heterogeneity of concrete and provides more insights on transport phenomena (e.g. water and salts ingress) in the material. Nevertheless, during the corrosion propagation stage, the polarization resistance remains the most important parameter to be determined as it provides quantitative information of the corrosion rate. If conventional three-electrode configuration methods can supply an accurate determination in the case of uniform corrosion, they often fail in the case of macro cell corrosion in field experiments. A four-electrode configuration without any connection to the rebar can rather be used for the non-destructive testing and evaluation of corrosion.

Javier Sanchez et.al (2016), [8] aims primarily to develop a modified version of the four-point method to measure resistivity in reinforced concrete structures with thinly covered rebar. Concrete quality can be tested on site by coring or non-destructive testing. This paper describes a method based on the four-point or Wenner procedure for measuring electrical resistivity, deployed on a bridge over the River Danube between Vidin, Bulgaria and Calafat, Romania. Due to the high reinforcement density in bridge members, a model had to be developed to measure resistivity in the concrete cover and the instruments conventionally used had to be modified.

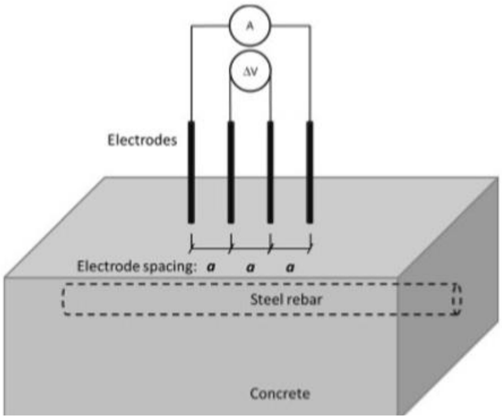

Figure 1: Wenner method for measuring resistivity in a reinforced concrete slab

Concrete durability can be determined based on electrical resistivity, a parameter readily and nondestructively measured on site. A modified version of the four-point or Wenner method was developed and applied to a bridge spanning the River Danube. The new procedure introduced a 'rebar factor', fb, to measure resistivity in reinforced concrete structures with thin concrete covers. The model findings showed that this factor is not dependent upon resistivity.

Ali Akbar Ramezanianpour et.al (2010), [12] Investigate the possibility of replacing the Rapid Chloride Penetration Test and water penetration test by the simple non-destructive surface resistivity test. The present study is an exploratory research concerned with the relationship of these methods. Based on the correlation of concrete resistivity with water penetration and Rapid Chloride Penetration Test (RCPT) results, two new models for relating these parameters are presented. Based on the correlation of concrete resistivity with water penetration and Rapid Chloride Penetration Test (RCPT) data, a relationship that can be used to estimate permeability of concrete from the measured resistivity values was discovered. Results show that although in concretes with similar cementations materials different relationships can be found, but generally because of different mechanisms of compressive strength and electrical resistivity, there is no appropriate relationship between them. Consequently, it is not recommended to use electrical resistivity as an indicator for evaluation of compressive strength.

Pratanu Ghosh et.al (2015), [9] examined the surface resistivity (SR) and the bulk electrical resistivity (BR) of concrete cylinders for several ternary mixtures at different testing ages. In addition, this study evaluated the influence of various significant parameters namely geometric size, probe spacing, replacement levels of silica fume and metakaolin in ternary based cementitious mixtures on the SR of concrete. New recommendation has been proposed for chloride ion permeability classification on the basis of electrical resistivity and compared with widely used Florida and Louisiana DOT classification. Overall, this study will enable researchers and state highway agencies to use nondestructive SR and BR measurement technique as a potential tool to evaluate ternary based high performance concrete (HPC) mixtures and predict the corrosion rate.

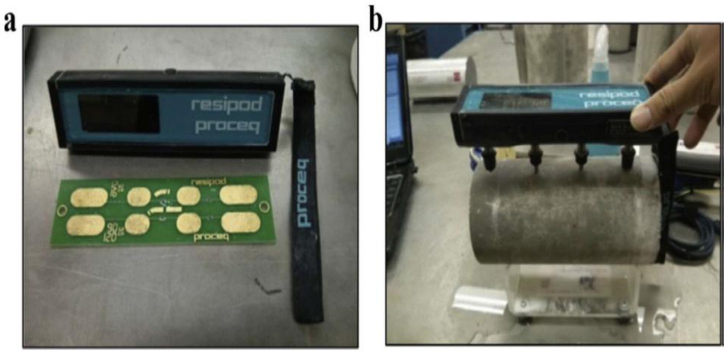

Figure 2: SR testing instrument with (a) 4-point Wenner probe instrument and (b) testing concrete specimen.

Kai Osterminski et.al (2012), [11] this paper presents resistivity data of concrete specimens up to an age of 17 years. An investigation was carried out of their development throughout the years in dependence of all main aspects influencing the magnitude and the development of the resistivity (climate, cement type, water/cement-ratio). Against the background of immense costs of repair or replacement of concrete structures degraded by reinforcement corrosion, a strong interest in industry and research can nowadays be found in the underlying processes and in possibilities to influence them. As a part of the reinforcement corrosion circuit, the resistivity of concrete is a decisive material parameter with regard to corrosion propagation, which itself is a time dependent process of many years of length. For this reason, a picture of the long term behavior of the resistivity of concrete could be of great value.

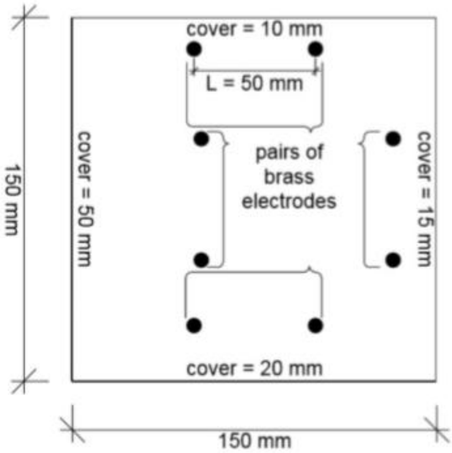

Figure 3: Electrode setup of two brass electrodes for each of the four cover depths in a cube specimen

Over 17 years of exposure, measurements have shown a continued increase of resistivity, which confirms that the hydration of slag particles in the cement continues for a very long time. The exposure to wetting and drying over about four years' time related to natural occurrence of precipitation (with its inherent temporal variation) after the previous exposure of the specimens for 13 years in a constant laboratory climate did not have a strong impact on the results of the resistivity at a cover depth of 50 mm. In other words, a medium depth in concrete, the previous history of exposure does not have a strong influence on the resistivity on the long term in a given environment.

In-Seok Yoon (2019), [2] 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. 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. The specimen used for the study was with size 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 and with different types of cement, water cement ratio and different curing conditions.

Table 1: Chloride Ions Penetrability

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

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.

Pejman Azarsa et.al (2017), [6] In this paper, the correlation between electrical resistivity and certain durability characteristics of concrete is discussed. These concrete characteristics include chloride permeability, corrosion rate, and compressive strength. Also, different approaches in the measurement of concrete resistivity including bulk and surface resistivity measurements are presented. This paper reviews the effect of several influencing parameters such as external environment (e.g. Temperature) and concrete mixture on the electrical resistivity. In addition, some of bulk and surface resistivity test setups (both of laboratory and field tests) conducted by authors are also presented.

In agreement with most studies, when there is an embedded rebar in the concrete, the electrical current field is distorted, and thus errors can result in the electrical resistivity measurements. To minimize this effect, it is suggested to place all electrodes perpendicular to the embedded rebar on the concrete surface and take at least five measurements, each a few millimeters in distance from one another. Also, a correction factor should be applied to resistivity measurements once rebar is present in concrete. Concrete resistivity is inversely related to chloride ingress, where lower resistivity indicated the area where chloride diffusion will be faster. A retardation of chloride can be taken into account through the introduced reaction factor. Furthermore, a strong correlation can be found between increasing electrical resistivity of concrete and the corrosion rate. The relationship can be seen when corrosion has initiated (active conditions). It will not be valid in the case of saturated concrete, where although the resistivity is low, the corrosion rate will be small because of lack of oxygen.

Erhan Guneyisi (2004), [14] experimentally investigate on the steel reinforcement corrosion, electrical resistivity, and compressive strength of concretes. Concretes having two different water–cement ratios (0.65 and 0.45) and two different cement contents (300 and 400kg/m^3) were produced by using a plain and four different blended Portland cements. Concrete specimens were subjected to three different curing procedures (uncontrolled, controlled, and wet curing). The effect of using plain or blended cements on the resistance of concrete against damage caused by corrosion of the embedded reinforcement has been investigated using an accelerated impressed voltage setup. The resistivity of the cover concrete has been measured non-destructively by placing electrodes on concrete surface. The compressive strength, electrical resistivity, and corrosion resistance of the concretes were determined at different ages up to 180 days. The results of the tests indicated that the wet curing was essential to achieve higher strength and durability characteristics for both plain and especially blended cement concretes. The concretes, which received inadequate (uncontrolled) curing, exhibited poor performance in terms of strength and corrosion resistance.

Ronaldo A. Medeiros-Junior (2015), [7] Investigate the evolution of concrete resistivity over time and, consequently, the pore network behavior, especially regarding the inclusion of cements with additions and long term data. The use of various cement types with different additions (blast furnace slag, fly ash, besides cements resistant to sulfate, and others), with different chemical compositions and physical characteristics is very common. Thus, there is a need to understand the behavior of the concrete resistivity with resistivity, over a period of 2 years, of unsaturated concrete with some cement used in Brazil, easing the use of resistivity in durability studies.

Concrete resistivity can be used to monitor the quality of concrete; this parameter expresses a relation with the permeability of the concrete and with the interconnectivity of the pore network; therefore, indicating the ease of penetration of aggressive agents into the concrete, directly related with the durability of such structures. This study showed no significant influence relations between w/b ratios 0.4, 0.5 and 0.6 on the electrical resistivity values of the concrete, for a same type of cement. However, the types of cement have a significant effect on resistivity. The cements with blast furnace slag (CPIII) and pozzolans (fly ash, CPIV) additions have a higher resistivity. This behavior is related with the effect of the refinement of concrete pores and the reduction of permeability due to additions. The cements with additions also have a higher resistivity increase over time, because the hydration reactions are more progressive compared with the pure cement clinker. Moreover, cement with the addition of small amounts of calcareous filler (=10% ground limestone, CPII) shows no significant difference from cement without additions (CPV). The best fit found for the evolution of resistivity over time was polynomial for all samples. Coefficients a, b and c of the quadratic equation were determined in this study to facilitate the estimation of the longterm electrical resistivity of unsaturated concrete. Coefficients of determination between 0.98 and 0.99 were found.

V. Ivica (2001), [15] Quantitative data on corroding steel reinforcement in reinforced concrete structures are undoubtedly very useful for evaluation of their service life and timely repairs. The method of electrode potential measurement is a convenient and simple test for this purpose, but it provides no quantitative data on corrosion rate and only information regarding active or passive state of steel reinforcement can be obtained. The paper shows here the possibility of obtaining quantitative data on degree of corrosion of steel reinforcement by a potentiodynamic method. The developed method is based on experimentally estimated mathematical relation between the results of potentiodynamic method and degree of corrosion of steel reinforcement. It is possible to calculate the degree of corrosion of steel reinforcement using this mathematical relation and the measured values of current density by the potentiodynamic method.

The purpose of the present study was improvement of the potentiodynamic method (PDM) for the measurement of corrosion rate. The improvement of PDM was based on the following: (i) to find the relationship between the proper PDM characteristic of the corroding reinforcement and the increase of corrosion sensor, ΔR measured by MER under the same conditions and (ii) to obtain a mathematical expression of the found relationship, giving the possibility of calculating ΔR using the results of PDM, and comparing the calculated ΔR values with those measured by MER. This paper shows here the possibility to estimate some quantitative data on the corroding steel reinforcement by means of potentiodynamic method and of a calculation approach. This is based on the experimentally found mathematical relationship between potentiodynamically measured current density, and corrosion degree of steel reinforcement measured by means of electrical resistance.

Ozkan Sengul (2014), [10] Investigate the relationship between chloride diffusivity and electrical resistivity for a group of concrete mixtures. An experimental study was carried out in which the electrical resistivity and chloride diffusivity of concretes were measured. Some of the factors affecting the resistivity were also investigated to provide more information. Thus, it was found that the chloride diffusivity can be controlled indirectly by the measurements of resistivity, and resistivity is a good indicator of concrete durability. A strong relationship between chloride diffusivity and electrical resistivity was obtained although different concrete mixtures and various testing ages were used. The experimental relationship between diffusivity and resistivity verify that electrical resistivity of concrete can be used as a durability indicator, and also for quality control and rapid classification of concretes. Results showed that environmental conditions and mixture characteristics significantly affect the electrical resistivity of concrete. Both the moisture and temperature conditions significantly affected the electrical resistivity of the concrete. Therefore, to obtain reliable and comparable data, moisture conditions and temperature should be kept constant. A classification of chloride resistance based on resistivity is proposed.

Tian Sua (2019), [3] This paper presents the experimental results of the influence of relative humidity (RH), temperature, fly ash content and chloride concentration on the relationship between concrete resistivity and the corrosion level of steel bar in concrete. The results show that the concrete resistivity decreases with the increase of corrosion level of steel bar under the same RH and temperature. The concrete resistivity decreases with the increase of RH and temperature, and the relationship between concrete resistivity and RH (temperature) is established. The concrete resistivity increases with the increase of fly ash content when the concrete cover thickness and the corrosion level of steel bar are the same, while it decreases with the increase of chloride concentration. The relationship between concrete resistivity and the corrosion level of steel bar in concrete with different chloride concentration (fly ash content) is established.

F. Hunkeler (1996), [16] This paper gives an overview of some of the more mechanistic aspects of the ionic conductance of mortar and concrete. It has been shown that not all water in mortar or concrete is conducting. The fractional volume of paste makes it possible to take into account the geometrically reduced cross-section of the conducting path due to the presence of aggregates. The influence of the pore structure of the paste itself and the chemical and physicochemical interactions of the water with the cement paste surface is much stronger than the geometrical effects. The combination of the above mentioned factors leads to an overall formation factor between the resistivity of concrete/mortar and the pore water in the paste of about 900 to 5000. The moisture content is much more important for the resistivity as well as for the corrosion rate than the chloride content.

Bo Yu, (2016), [4] In order to overcome the disadvantages of traditional deterministic methods, a probabilistic evaluation method to assess the corrosion risk of steel reinforcement in concrete was proposed based on the probabilistic prediction model of concrete resistivity. The influences of major influential factors including water-to-cement ratio, chloride content, ambient temperature and ambient relative humidity on concrete resistivity were investigated first. Then a probabilistic prediction model of concrete resistivity in terms of the above major influential factors was developed by using the Bayesian theory and the Markov Chain Monte Carlo (MCMC) method. Meanwhile, the evaluation criterion for corrosion risk of steel reinforcement based on concrete resistivity was proposed according to the relationship between concrete resistivity and corrosion rate of steel reinforcement. Finally, a probabilistic evaluation method for corrosion risk of steel reinforcement in concrete was developed by means of the proposed probabilistic prediction model of concrete resistivity. Analysis results show that the proposed probabilistic evaluation method can not only identify the dominant risk of reinforcement corrosion, but also determine the probabilities of steel reinforcement under different corrosion risk levels (e.g. negligible, low, moderate, and high), which could avoid the misjudgment of corrosion risk of steel reinforcement often encountered by the traditional deterministic evaluation methods.

III. CONCLUSION

Through an extensive literature review, this paper identifies several factors which might have potential influence on the electrical resistivity of concrete. Correlation between concrete electrical resistivity and its certain durability characteristics such as chloride diffusivity, compressive strength, and corrosion potential/rate was discussed in this paper. Concrete resistivity is inversely related to chloride ingress, where lower resistivity indicated the area where chloride diffusion will be faster. Furthermore, a strong correlation can be found between increasing electrical resistivity of concrete and the corrosion rate. The relationship can be seen when corrosion has initiated (active conditions). It will not be valid in the case of saturated concrete, where although the resistivity is low, the corrosion rate will be small because of lack of oxygen. In addition, concrete compressive strength and its electrical resistivity have a direct relationship with each other as both directly depend on the porosity of the matrix at early age. However, at a later age, the conductivity of the pore solution and degree of concrete saturation both influence this relationship. No practical relationship was identified in the literatures between compressive strength and electrical resistivity. It can be concluded that still large range and scatter exist for correlation between durability and concrete resistivity. Also, effect of moisture state and temperature as well as corrections to corrosion rate measurements should be considered during an investigation on finding correlation between resistivity and durability.

FURTHER SCOPE

In this study, influence of various parameters on resistivity is being studied. Grade of concrete, curing medium and rebar presences influences electrical resistivity. However, it is still recommended to perform additional tests for determine effect of different rebar diameters, different grade of concrete, a wider range of covers and presence of lateral and longitudinal rebars during corrosion. Also want to find the relationship between resistivity and rate of corrosion of concrete members which is submerged in sea.

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