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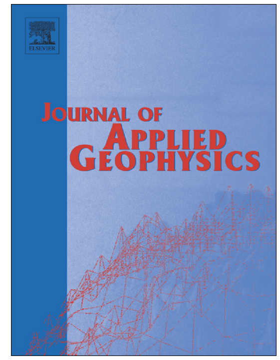

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Determination of the Reinforced Concrete Strength by Electrical Resistivity depending on the Curing Conditions

Nevbahar SABBAĞ[1] and Osman UYANIK[1*]

ABSTRACT

In this study, change of the electrical resistivity values was investigated on reinforced and unreinforced concrete samples that were designed in different strength of the dry and water saturated conditions. For this purpose, studies were conducted with 150x150x150 mm cubic samples of 9 different concrete designs. A piece of 10, 14 or 20 mm diameter reinforcement was placed in the middle of concrete samples and 18 samples were prepared for all types of them and 9 samples for the unreinforced samples. Some of the prepared these samples were subjected to the water cure and the other part of the samples were kept in the air cure. The potential difference measurements were made by electrical resistivity method on different surfaces of the sample at specific time periods of during the 90 days and apparent resistivity values of the samples were determined. Furthermore, the concrete strength was determined from average of 3 samples by uniaxial compressive strength test of each sample on 7th, 28th and 90th days. Changes of the apparent resistivity and concrete strength values that obtained from these conducted studies were investigated to depending on time. At the same time, the relationship between uniaxial compressive strength and the apparent resistivity was revealed in case of the samples' being in water or air cure. Accordingly, it was stated that the different curing conditions have an effect on the apparent resistivity of concrete and concrete strength. Therefore, while the apparent resistivity of the concrete design having different strengths increased depending on increasing concrete compressive strength of samples in the water cure; it reduced in the air cure. This research is important in terms of both time and being economical by providing a non-destructive approach to the determination in-situ of the concrete strength of the water or gas saturated old and new concrete structures.

Keywords: Reinforced concrete, reinforcement, resistivity, uniaxial compressive strength, Concrete, water cure, air cure

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1. INTRODUCTION

Non-destructive geophysical methods are effectively used for reducing the damage of concrete and to obtain economic results in terms of time and financial. With these methods, it is possible to detect the faults of the materials during manufacturing or after a certain period of use (cracks due to corrosion or abrasion, voids in the internal structure, reinforcement detection, etc.). Some researches has also been used several methods combined. The problems related to the structure have increased the importance of structure analysis. Some of the main important targets of the structural analyzing investigations by using non-destructive geophysical techniques such as electrical resistivity technique (ERT) is used for determine the electrical properties of concrete and reinforcement corrosion (Feliu et. al., 1996; Lataste et. al., 2002; Polder and Peelen, 2002; Güneyisi et. al., 2005; Ferreira and Jalali, 2006; Sadowski, 2010; Plooy et. al., 2013; Ghosh and Tran, 2015); induced polarization (IP) is used for obtaining information about concrete sample structure (Altundaş, 2010); electromagnetic (EM) is used for determination presence of reinforcement (Zhao et. al., 2014; Moustafa et. al., 2016); ground-penetrating radar (GPR) is used for display of reinforcement fittings in columns and beams, determination of existing building foundation type and discontinuity investigations in columns and beams (Buyle-Bodin et. al., 2003; Sbartai et. al., 2007; Cassidy et. al., 2011); seismic ultrasonic wave technique is used for determine the quality of concrete, internal cracks as well as the deterioration in the concrete and estimation of the concrete strength (Pimenov et. al. 1972; Martin and Forde, 1995; Yeih and Huang, 1998; Naffa et. al., 2002; Kewalramani and Gupta 2006; Lorenzi et. al. 2007; Trtnik et. al., 2009; Uyanık et. al., 2011; Uyanık, 2012; Uyanık and Tezcan, 2012; Uyanık et. al., 2012); Petro and Kim, 2012; Pfister et. al., 2014; Sabbağ and Uyanık, (2016a; 2017)); Schmidt Hammer is used for determining concrete strength (Ergün and Kürklü, 2005; Jain et. al., 2013); microtremor is used for determining the foundation type (Uyanık, (2014; 2015); Uyanık et. al., 2015), dynamic behavior of building (Navarro and Oliveira, 2008), construction period (Timur et. al., 2015) and seismic effects on building structure (Sanches et. al., 2002); radioactivity (RA) is used for the effects of construction materials radioactivity quantities on human health (Uyanık et. al., 2013; Kılınçarslan et. al., 2011; Abbasi, 2013; Akkurt et. al., 2013; Işık et. al., 2017). From among them the impact of reinforcement and curing conditions to the concrete strength can be determined by measuring resistivity of concrete. In this case, valuable data can be obtained without any damage to the structure so as to deal with problems such as the concrete strength of the existing structure and the status of the reinforcement in the concrete. Changes in the electrical properties of the concrete can be monitored in order to evaluate the thickness, density, moisture content and temperature variations of the concrete. Furthermore, apparent resistivity values can vary depending on the curing conditions of concrete.

As an alternative, electrical resistivity measurement can be used for the performance-based evaluation of concrete (Layssi et al., 2015). For this purpose, many researchers have investigated properties of concrete in-situ or in laboratory by electrical resistivity method (Morris et. al., 1996; Silva et. al., 2006; Plooy et. al., 2013; Hornbostel et. al., 2013; Chen et. al., 2014; Layssi et. al., 2015; Sabbağ and Uyanık, 2016a; Uyanık and Sabbağ, 2016). Electrical resistivity technique (ERT) is widely used for investigation of the effect of sample shape on changes in the electrical properties of concrete and also hydration degrees (Ferreira and Jalali, 2006; Ghosh and Tran, 2015), the availability of electrical resistivity method in the structure which contains cracks and fracture (Lataste et. al., 2002), in order to determine the properties of the concrete (Morris et al., 2002), investigation of the concrete resistivity depends on the properties of microstructure of the concrete and conductivity of the solution in the pores (Polder, 2009), investigation of the chloride permeability of concrete and the effect of compressive strength (Ramezanianpour et. al., 2011), investigation development of specimens throughout the years in dependence of all main aspects influencing the magnitude and the development of the resistivity (climate, cement type, water/cement-ratio) (Osterminski et. al., 2012), affection presence of reinforcement in the concrete in-situ (Garzon et. al., 2014; Chu and Chen, 2016), investigation of influential parameters such as environmental conditions and presence of reinforcement and cracks on measuring electrical resistivity of concrete (Azarsa and Gupta, 2017).

According to conducted studies, there is a strong relationship among porosity, water content and resistivity of the concrete (Silva et. al., 2006; Plooy et. al., 2013; Chen et. al., 2014; Sabbağ and Uyanık, 2016b; 2016c). It was concluded that electrical resistivity measurements is an appropriate method for monitoring chloride permeability and the quality control of obtained concrete during the manufacturing process of the structure (Şengül et. al., 2007). The development of the resistivity devices can be used for studies related to the determination parameter of the concrete (especially water and chloride content and porosity) in future. In addition, by using of these devices with combination of the electrical tomography and electromagnetic methods such as capacity meter and radar are expected to allow define characteristics of the concrete due to chloride, water and pore structure in-situ application non-destructively (Şengül et. al., 2007; Polder 2009; Ramezanianpour et. al., 2011; Plooy et. al., 2013; Garzon et. al., 2014; Ghosh and Tran, 2015).

The effect of curing condition and reinforcement diameter change the resistivity measurement results. Therefore, in this study, 9 concrete design of having different strengths were prepared and samples of the prepared in laboratory conditions were formed as unreinforced and reinforced cubic concrete samples including 10, 14 or 20 mm diameter reinforcement. Electrical resistivity test were performed for investigate the change of electrical resistivity values on the samples that exposed to the water or air cure to depending on the water or air saturation of the these samples pores on 7th, 28th, 41st, 56th, 65th, 72nd and 90th days and uniaxial compressive strength test were made on 7th, 28th and 90th days. Correspondingly, relationships between electrical resistivity and compressive strength were put forward by depending on curing conditions and reinforcement diameter. As a result of this study, it was determined that there is not only an increasing relationship but also a decreasing relationship between electrical resistivity and concrete strength depending on the curing conditions of the concrete.

2. METHODS

2.1. Destructive Uniaxial Compressive Strength

Uniaxial compressive strength is a direct method for the determination of concrete strength. However, this process gives damage to the structure. According to the validity standards, uniaxial compressive strength is determined by taking various sizes core samples from the existing structure. Making and evaluation of compressive test by taking core samples from the structure will enable us to get some information about the quality of the existing concrete structure. In the test, iron apparatus that its diameter was up to sample diameter and thickness was up to the sample radius were placed between the top and bottom of sample which placed between hydraulic press plates (Figure 1). In this way, homogeneous dispersion of the load on the sample is obtained. In this case, load which applied at the time of the sample breakage is P and the surface area of the sample is A, uniaxial compressive strength is obtained the form of (σ_b); P/A. Cubic samples edges that perpendicular to the casting direction are positioned as contact to the plates of the test machine during the compressive strength test. Compressive strength varies with discontinuities and stresses that perpendicular or parallel direction to the substrate surface. Strength of perpendicular direction to the discontinuity surface is greater than the strength of sample obtained in parallel direction (Köse and Kahraman, 1998; Sabbağ, 2016; Sabbağ and Uyanık, 2016a).

The concrete compressive strength is affected by changes in loading speed. As long as the speed of stress applied to concrete sample increases, (as the load is applied in a longer period) the sample is broken down under a smaller stress. In other words, the compressive strength on the sample that obtained in the low-load speed is lower. This case is resulted from a certain amount of creep due to longer duration on the sample. However, applying the high loading rate is lead to break of the samples, that is, higher compressive strength value is obtained (Erdoğan, 2010; Felekoğlu and Türkel, 2004; Sabbağ and Uyanık, (2016b; 2016c)).

In this study, average of measurements were taken by performing uniaxial compressive strength test on the 3 samples of the crushing on 7^{th}, 28^{th} and 90^{th} days in order to observe the changes in the compressive strength depending on time. The rate of load application on the samples was applied an average 13.5 kN/s (0.6±0.2MPa/s) for 150x150x150mm sizes cubic samples in accordance with TS EN 12390-3. 150x150x150mm sizes reinforced and unreinforced concrete cubic samples were used to obtain the compressive strength. Concrete is filled with two layers inside the cubic mold and each layer is compressed by means of a vibrator or by a steel bar. After molds filled with concrete are waited for 24 hours, they are removed from the mold and are subjected to water and air cure. While concrete compressive strength was obtained, uniaxial compression test was performed by reinforced sample of contain 10, 14 or 20mm diameter reinforcement was facing up to side surface.

2.2. Non-destructive Resistivity Method in Geophysics

Potential difference measurement as non-destructive method is used for determination of quality of the concrete rapidly and successfully in the study area. Error rate is around 5% in the conducted studies. A good association can be made by the electrical resistivity with the strength indicators such as diffusion coefficient, permeability coefficients, capillary absorption and porosity. Thus, large areas in the building will be measured indirectly. Prediction of electrical resistivity depending on the time and temperature can be used for determination of the resistance values of modern designs (Ferreira and Jalali, 2006; Lim et. al., 2011).

Every material transmits an electric current. The conductivity or resistivity of concrete is depended on the pores of distribution in the concrete, potential water content and the amount of soluble salts. The properties of concrete can be estimated by evaluation of the anomaly that occurs with conductivity measurements of inhomogeneous media. A small resistivity meter that was developed for in-situ measurement of concrete and worked by 4-electrode Wenner array systems are used swiftly and in a wide area (Candansayar, 2015). A linear array is used as electrode interval to be "a ". In this method, potential measurements are performed by two electrodes of the outer with giving currents to two inner electrodes (Başokur, 2004). When probe is bumped to concrete surface, cycle of the current exchange between electrodes and potential measurement is performed in the electronic control unit. Electronic contact provider which made of water-saturated foam pillow is used for providing the electrical conductivity. Resistance measurement devices produced by different companies are recently suggested for this purpose. The resistance value of this device is given as kΩcm (Figure 2). Additionally, the device also provides the reliability of the results as % (BRE, 2000; Polder, 2009; Simon and Vass, 2012).

Porous materials absorb to water in the air and conductivity greatly decreases with decreasing relative humidity. OH^- concentration decreases during the carbonation in case of low relative humidity. This situation increases the conductivity of the water in the pores. Hence, the electrical resistivity of concrete is substantially affected by porosity, moisture and resistance of the liquid in the pores (salt transmission to water in the pores). When water filled the pores containing dissolved salt, concrete become electrically conductive. Electrical resistivity of the concrete depends on water/cement ratio (conductivity in the pores), porosity and distribution of pore size, volume and type of the cement, temperature and humidity. Cement chemistry, cement components, water/cement ratio and additional materials used for cementation and use of mixtures also affect the microstructure of the concrete and solution chemistry of void, therefore impressed to the resistivity. There is a strong relationship between electrical resistance and durability depending on the used concrete age. In addition to this, the temperature has a great effect on the concrete resistivity (Ferreira and Jalali, 2006; Silva et. al., 2011; Simon and Vass, 2012).

The resistivity and location of reinforcing bars are often associated with the durability of concrete (Şengül et. al., 2008; Ferreira and Jalali, 2010). The electrical resistivity can be used for determination of concrete durability and quality. The resistivity of concrete can vary in wide limits such as from 1 to 10^4 kΩm. Low-frequency alternative current is given by two outer electrodes and the voltage drop is measured by two inside electrodes into the 4 electrode Wenner array test (Figure 3). Measurements are made to be with 5 cm electrode interval. Measurements are taken from every surface vertically and the average of them is calculated (Silva et. al., 2011).

Providing that length is defined as L and area is A, potential difference (V) occurred in material by passing of alternative current (I) between two parallel electrodes, the resistivity of the cubic unit is calculated from Equation 1.

$$\rho_a = \frac{V.A}{I.L} \qquad (1)$$

When an alternative current was applied from the outer electrodes (generally in 50-100 Hz frequencies and sinusoidal) according to Wenner electrode array, resistivity value was found by measuring of the potential difference between the middle electrode (BRE, 2000; Polder, 2009).

$$\rho_a = \frac{2\pi a V}{I} \qquad (2)$$

While resistivity measurements are made on concrete, one of the most important problems is derived from the fact that the properties of the concrete are affected by changes in the environment. The most important factor that affects the resistivity of concrete is moisture content of the concrete. As the humidity rate in the concrete increases, resistivity value decreases. Particularly, the changes in the moisture have a very large effect on readings in-situ measurements. However, humidity variations in the outer portion of the concrete do not effect to results significantly. Therefore, the electric resistivity method can be used as an indirect measurement method for determining the saturation of the concrete.

Data collection process of the electrical resistivity method can be made easily in a very short time by resistivity devices. Equipment is quite cheap and due to the fact that measurements could be taken quickly, it cannot lead to loss of time. In the conducted studies, according to the objectives and target structure different electrode arrays can be used. Furthermore, using of this method with other methods such as natural potential method would be much more useful. Despite these advantages, method has some disadvantages, as well. Particularly, the position and length of the measurement profiles and location of the measuring points also affect the response of wanted structure. Therefore, the choice of them is very important. Concrete is made from cement and aggregates and these materials have different resistivity values. Hence, the distance between the electrodes must be large enough so that measured values could define the average of concrete resistivity. The method can give incorrect results in surfaces with very high resistivity and humidity areas (Carino, 1999).

Nowadays, non-destructive methods are used in studies in order to minimize the damage that core samples of taken from the structure created. In this study, measurements were made on the concrete samples by electrical resistivity device at specific time intervals during the 90 days it will provide an approach to make comments about strength and the quality.

3. PREPARATION of SAMPLES

Concrete can be defined as composite structure material that is obtained by the mixture of different size of aggregates which are mineral materials such as sand, gravel and crushed stones with cement in order to paste them and water, then this mixture can harden by gaining strength. Crushed stone aggregate was used as the aggregate type for this study. Rocks taken from the quarry near the Antalya were crushed into desired sizes by stone crusher, so that the aggregate was formed.

Unit volume mass, density, mass of water absorption, volume of water absorption, losing of pressure after freeze, determination of strength against to frost by sodium sulfate, Los Angeles abrasion loss laboratory experiments were made on the samples of prepared by using crystallized limestone, marble etc. as the material of rock supplies area. After these experiments, Aggregates were prepared by using 25% coarse gravel, 23% middle gravel, 52% sand. During the preparation of the designs, CEM II / B-LL composite Portland cement (limestone (total organic carbon): 0.2%) was used as a kind of cement. Air-entraining admixture of Aermix and super plasticizer concrete admixture Fluicon was used as chemical additives. The mixtures were prepared by using tap water potable. Slump test value is taken as 12cm for all mixtures.

Studies were conducted with preparations of reinforced and unreinforced cubic samples of 9 different concrete designs. While 324 samples in total with 9 samples for each type that including a piece of 10, 14 or 20 mm diameter reinforcement and unreinforced cubic samples were subjected to water cure, 243 samples in total with 9 reinforced cubic samples including pieces of 10, 14 or 20 mm diameter reinforcement were subjected to air cure. By taking two cross measurements from every surface with total 8 measurements on 4 different surfaces of the samples by electrical resistivity method on 7^{th}, 28^{th}, 41^{st}, 56^{th}, 65^{th}, 72^{nd} and 90^{th} days, an average of resistivity values was calculated. In addition to this, each of 3 samples was measured by Uniaxial compressive strength on 7^{th}, 28^{th} and 90^{th} days and the averages of them were calculated (Table 1).

In conducted study, prepared 9 concrete mixture designs were rodding in 25 times at two stages, and then they were placed in plastic cubic mold. The samples that were hold in the mold during 24 hours to harden were removed from the mold then they were divided into groups and placed where they will be cure. While some of samples were subjected to the water curing in a cure pool; some of them were subjected to the air cure by waiting outside (Figure 4).

The samples were prepared to measure each design in specified time periods; weight measurements and volume calculations are made for determination of the density. Resistivity measurements are made as denominated kΩcm by electrical device. It is calculated by taking the average of 8 values in measuring the cross measurements in two sizes on 4 surface of cubic samples with an angle of 90^o. Compressive strengths of samples were determined as denominated MPa by Compressive Strength test measurement of taken in the specified time periods. Conducted studies on samples of prepared as reinforced and unreinforced for 90 days were interpreted by using the data that are obtained according to the flow diagram of shown below (Table 2).

Reinforced and unreinforced samples exposed to water and air cure during the specific time periods determined by electrical resistivity and uniaxial compressive strength were firstly evaluated individually and then together. Thus, opportunity has been obtained in order to make a common comment.

4. EVALUATIONS

According to the electrical resistivity results that were obtained from prepared unreinforced and reinforced samples including 10, 14 or 20 mm diameter reinforcement and then 9 different concrete design exposed to water or air curing on 7th, 28th, 41st, 56th, 65th, 72nd and 90th days and uniaxial compressive strength results that were obtained on 7th, 28th and 90th days, maximum, minimum and average data have been shown in Table 3.

4.1. Change of resistivity and uniaxial compressive strength of water saturated reinforced and unreinforced concrete samples depending on time

In the studies carried out, electrical resistivity increases as the age and hydration level increase according to the measurements made over 90 days (Ferreira and Jalali, 2006; Ghosh and Tran, 2015). The electrical resistivity of the concrete is strongly dependent on the moisture content and environmental effects (Silva et al., 2011). As humidity increases, the resistivity value decreases. Especially in-situ measurements, the changes in the humidity condition have a great effect on reading. However, moisture changes outside of the concrete do not significantly affect the results. For this reason, electrical resistivity method is an indirect measurement method in determining the saturation of concrete (NEA/CSNI/R, 2002). It has been observed that depending on the sample geometry and electrode openings, the reinforcement were reduced the resistivity values (Garzon et al., 2014).

In our case, time-dependent changes in electrical resistivity of saturated unreinforced and reinforced cubic samples including a piece of Ø10, Ø14 or Ø20 reinforcement of 9 different designs that were exposed to the water cure were shown in Figure 5. As a result of conducted studies for 90 days, generally unreinforced samples have a higher resistivity value than reinforced samples and apparent resistivity values were observed to increase with water saturation depending on time. Generally resistivity value of unreinforced samples was found out to be higher in the water cure. Lower resistivity values were obtained as reinforcement diameter in sample increased. This situation results from the fact that reinforcing bars have low resistivity (approximately 10^{-8} kΩcm).

Ramezanianpour et al. (2011) found that there is a strong relationship between porosity and resistivity of the concrete in their work. In this study, while the continuity of this increase was more clearly observed in the first 4 designs with plenty of pores (Figure 5-a, b, c, d); a slight decrease or fixing was observed in the resistivity values along with gradual decrease in pores amount on 65th or 72nd days. While resistivity values of lower strength water-saturated concrete that is exposed to water cure were generally varied in the range of 4-8 kΩcm, resistivity values vary in the range of 9-17 kΩcm in high-strength concrete.

According to this study, compressive strength of the water saturated samples increased as the strength of prepared designs increased. At the same time, since the samples were cured in the water depending on time, an increase was observed in compressive strength with regard to increased water saturation. When uniaxial compressive strength results obtained on 7th, 28th and 90th days were compared with each other, while increment was less in low-strength concrete (Figure 6-a, b, c), it was greater in high-strength concrete (Figure 6-d, e, f, g, h, i). While Uniaxial Compressive strength values of water-saturated low-strength concrete that was exposed to water curing were generally varied in the range of 3-23 MPa, it varied in the range of 35-70 MPa in high-strength concrete. When the strength of the unreinforced samples in this group was compared to reinforced concrete samples including 10, 14 or 20 mm reinforcement diameter, while the strength of unreinforced was much less in low-strength design, it was found out that it was higher as strength of the design increased. This situation is emerged due to the increasing amount of pores in the samples.

4.2. Change of Resistivity and Uniaxial Compressive Strength of the Dry-Reinforced Concrete Samples

When the resistivity changes of the dry concrete samples that were exposed to air cure had been examined depending on time, it was observed that there was a tendency to decrease in resistivity (Figure 7). However, irregularities observed in the some samples that performed resistivity measurements on 7th, 28th, 41st, 56th, 65th, 72nd and 90th days are due to the porous structure on the surface. Because the electrodes must be on a smooth and clean surface in the resistivity measurements of taken in accordance with Wenner array by 4-point electrode method. However, cellular structures on the surface of samples in low-strength designs and the roughness voids and pores on the surface of some samples in high-strength designs have occurred because of workmanship faculties such as transport, mixing, placement, etc. This situation made getting accurate measurements difficult. Therefore, the average apparent resistivity values were obtained by taking two orthogonal measurements in the each surface of the cubes. While resistivity values of low-strength dry concrete that were exposed to air curing generally varied in the range of 20-70 kΩcm, it varied in the range of 14-30kΩcm in high-strength concrete. Lower resistivity values were obtained as reinforcement diameter increased in the air cured samples as well as the water cured samples.

When the change in compressive strength of reinforced concrete in air cure is analyzed, a general tendency to decrease is observed. As samples dried depending on time, a decrease in compressive strength was observed. When uniaxial compressive strength results obtained on 7^{th}, 28^{th} and 90^{th} days were compared with each other, while decrement was less in low-strength concrete (Figure 8- a, b, c), it is higher in high-strength concrete (Figure 8-d, e, f, g, h, i). While Uniaxial Compressive strength values of air-saturated low-strength concrete that were exposed to water curing generally varied in the range of 4-20 MPa, it varied in high-strength concrete in the range of 40-70 MPa. Strength values of small (10 mm) and big (20mm) diameter reinforcement samples were compared in Figure 11. According to this, the strength of sample increases by increasing reinforcement diameter in low-strength designs (Figure 8- a, b, c). However, in great-strength designs (Figure 8- d, e, f, g, h, ı) decrease the strength of sample by increasing reinforcement diameter.

4.3. Relationships between Electrical Resistivity and Uniaxial Compressive Strength

The resistivity decreases as the water/cement ratio increases and the conductivity increases (NEA/CSNI/R, 2002). There is a strong relationship between electrical resistivity and durability according to the age of the used concrete (Ferreira and Jalali, 2006, Simon and Vass, 2012).

According to this study, uniaxial compressive strengths of reinforced and unreinforced samples in water cure are presented in Figure 9 depending on the electrical resistivity changes. Accordingly, it was observed that there is a logarithmic positive relationship between electrical resistivity and strength of the sample in water cure (Equation 3). Furthermore, compressive strength increases with regard to increase the sample resistivity.

$$\sigma_b = 57.2Ln(\rho) - 84.3 \qquad R^2=0.92 \qquad RMSE=6.3 \qquad (3)$$

Uniaxial Compressive Strength of air cured reinforced samples were presented in Figure 10 depending on the electrical resistivity changes. When these changes were shown, each of the design samples including different diameters reinforcement were shown separately. Accordingly, a negative exponential relationship was observed between electrical resistivity and strength of the air-cured samples. Compressive strength is decreasing exponentially with regard to increase in the resistivity of samples. This empirical relationship is presented in Equation 4.

$\sigma_b=43.16(10^4)\rho^{-3}$ R2=0.96 RMSE=6.5 (4)

Chen et al. (2014) were studied on air dried specimens of having 40% or 80% relative humidity. According to these researchers, the resistivity was highly related with the compressive strength. In their study, results showed that the resistivity was increased with the increased compressive strength. However, in this study relationships between uniaxial compressive strength and electrical resistivity of samples in the water and air curing were presented together in Figure 11. Accordingly this situation, while uniaxial compressive strength was increased with the increased electrical resistivity of water saturated samples it was decreased with the increased electrical resistivity of the air saturated samples. Therefore, the above statement is partially true because it is not generally available in the all cure condition. Figure 11 was provided to compare changes between uniaxial compressive strength and electrical resistivity of reinforced samples by considering curing conditions. According to this, while electrical resistivity values in low-strength concrete gave low values (4-6 kΩcm) on the water cure, they were high values (32-48 kΩcm) on the air cure. In this case, water and air cure could be distinguished by apparent resistivity values in low-strength concrete. However, apparent resistivity values obtained for water and air cure exhibited a cluster at the upper side of the graph and therefore they cannot be readily distinguished in terms of the strength of the design within themselves, it was observed that it could be only distinguished based on differences in curing conditions.

The electrical resistivity value of cube samples in the water and air cure was conducted to compare in Figure 12. According to the results of the electrical resistivity of the sample in dry form is higher than water saturated samples of the same design. This case could reveal how electrical resistivity was affected by cure conditions in which there are samples prepared for the same design and including 10, 14 and 20mm diameter reinforcement. A similar situation can be also seen in Figures 5 and 7. While resistivity values decrease with regard to water saturation in samples belonged to the same design, resistivity values increase as samples dry and the pores inside it fills with the air.

While water and air cured samples were compared, the difference between the resistivity values of the low-strength samples was higher, but the resistivity values of high-strength samples were closer to each other. This situation is due to the porous structure of the sample. As the pores in the low-strength samples fills with water, quite low resistivity values are obtained while as the pores fills with air, quite high resistivity values are obtained. When it was compared to the low-strength samples, since the porosity was less in the high strength samples as shown in Figure 12. When taking into consideration the situation being filled with water or air it was quite obvious to make less distinction in resistivity.

The relationships between electrical resistivity of cube samples in water and air cure and including 10, 14 or 20 mm diameter reinforcement and Uniaxial Compressive Strength were shown separately, depending on the reinforcement diameter (Figure 13). Accordingly, the strength of the sample containing larger diameter fittings were also higher corresponds to the same resistivity values. Associations of the samples were separately obtained for each of reinforcement diameter in the water cure (Figure 13a).

$\sigma_b = 55.6Ln(\rho) - 83.5$ R^2=0.96 RMSE=4.5 (5)

$\sigma_b = 54.6Ln(\rho) - 77.8$ R^2=0.89 RMSE=7.2 (6)

$\sigma_b = 55.3Ln(\rho) - 78.9$ R^2=0.90 RMSE=6.7 (7)

The relationship between electrical resistivity of cubes in air cure and including 10, 14 or 20 mm diameter reinforcement and Uniaxial Compressive Strength were shown separately in Figure 13b depending on the reinforcement diameter. Accordingly, the strength of the sample containing larger diameter fittings were also lower corresponds to the same resistivity values.

$\sigma_b = 220553\rho^{-2.8}$ R^2=0.98 RMSE=6.1 (8)

$\sigma_b = 430029\rho^{-3}$ R^2=0.97 RMSE=6.1 (9)

$\sigma_b = 2000000\rho^{-3.5}$ R^2=0.96 RMSE=7.9 (10)

The relationship between electrical resistivity of cubes in water and air cure including 10, 14 or 20 mm diameter reinforcement and Uniaxial Compressive Strength were shown together in Figure 14 depending on the reinforcement diameter. Thus, a correlation has improved between electrical resistivity and the results of uniaxial compressive strength for cubes by taking into consideration cure situation and reinforcement diameter. The obtained curve of the samples including 10mm diameter reinforcement was much more above in relationships. Thus, as the reinforcement diameter gets smaller, it can be observed that compressive strength of the samples increase.

$$\sigma_b = \frac{5000}{\varnothing^{0.04}\rho^{0.4}\left(\frac{\rho}{16}+\frac{16}{\rho}\right)^{4.5}} \qquad R^2=0.92 \qquad RMSE=6.2 \qquad (11)$$

4.4. Change of Electrical Resistivity Depending on the Measurement Direction

In concrete theory and practice considered that concrete exhibit isotropic electrical resistivity, that is, the measured resistivity is no direction-dependent. However it is known that electrical current spread through concrete with different conductivity in different directions due to a spatial ordering of grains, bedding planes, air or water saturated voids, joints or fractures etc.

In different directions on the surface of the all cubic samples which obtained from 9 different designs resistivity values were obtained to check whether it changes depending on the direction of measurement. Resistivity values of obtaining from different surface and different direction of water and air group samples were compared (Figure 15). High values of RMSE error was obtained especially in the air group, when analyzed the direction-dependent change of the resistivity value of the water and air groups. The reason for this, can also originate from obtaining greater resistance value depending on the direction distribution of the air-filled pores of cubes.

5. CONCLUSION and DISCUSSION

In the result of the fracturing with uniaxial compressive strength test of reinforcement concretes that are performed water or air cure; while the reinforcement concrete strength value increases as reinforcement diameter increases in loose strength concretes, high strength concretes decrease as reinforcement diameter increases. According to the work done in general, the increase in the electrical resistivity of the concrete also increases the compressive strength, taking into account only the samples in the water environment (Chen et al., 2014). However, curing conditions have an important effect on the electrical resistivity (Ferreira and Jalali, 2006; Simon and Vass, 2012). Especially when the existing structures are assessed in situ, whether they are moist or dry will change the measurement results. For this reason, researchers such as Polder (2009) do not recommend using the electrical resistivity method in evaluating the concrete pressure resistance. However, the change in resistivity due to curing conditions can be clearly demonstrated in this study.

While determining the electrical resistivity of concrete designs having different strengths and curing conditions, the resistivity increased due to the increase in the compressive strength of concrete samples in the water cure; it reduces in the air cure. When compared to samples of the same design, resistivity values decreased with water saturation, as long as the sample dried and air fills in the pores depending on time, accordingly this, resistivity values also increased.

A positive logarithmical relationship was observed between electrical resistivity and strength of reinforced and unreinforced samples in the water cure. Compressive strength increases with regard to the increase in resistivity. Relationships of reinforced cubic samples in the water cure between electrical resistivity and Uniaxial Compressive Strength can be defined differently depending on the reinforcement diameter. Accordingly, correspond to the same resistivity value; as long as the samples of containing greater diameter reinforcement, the strength were also higher.

Cure conditions to which the samples are exposed have an impact on the concrete compressive strength. As the samples dry time-dependently, a decrease in compressive strength is also observed. When interpreting relationships between electrical resistivity and Uniaxial Compressive Strength of reinforced cubes in the air curing, depending on the reinforcement diameter, strength was also lower in containing greater reinforcement diameter of samples correspond to same resistivity values. The results of the electrical resistivity in the dry form of the sample are higher than the sample saturated with water. This case revealed how electrical resistivity in samples prepared for the same design and including 10, 14, 20 mm diameter reinforcement is affected by cure conditions. Electrical resistivity varies depending on the measurement direction, especially in dry samples.

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TABLE CAPTION

Table 1. Prepared examples and applied measurement (T = Design, Ø = reinforcement diameter W = weight, δ = density, ρ = apparent resistivity, σb = Uniaxial compressive strength)
Table 2. Flowchart of showing the operation carried out on the reinforced and unreinforced samples
Table 3. Results of electrical resistivity and uniaxial compressive strength of samples cured in water and air

FIGURES CAPTIONS

Figure 1. Uniaxial Compressive Strength device and measuring of sample strength

Figure 2. Performing resistivity measurements with electrical equipment having 50 mm electrode opening.
Figure 3. Measurement on samples by the electrical resistivity method
Figure 4. The samples of the water and air cure
Figure 5. Time-dependently apparent resistivity changes of unreinforced and reinforced cubic samples including 9 different designs with Ø10, Ø14 or Ø20 reinforcement in the water cure group.
Figure 6. Time-dependently uniaxial compressive strength changes of unreinforced and reinforced cubic samples including Ø10, Ø14 or Ø20 reinforcement of 9 different designs in the water cure group
Figure 7. Time-dependently apparent resistivity changes of reinforced cubic samples including Ø10, Ø14 or Ø20 reinforcement of 9 different designs in the air cure group
Figure 8. Time-dependently uniaxial compressive strength changes of unreinforced and reinforced cubic samples including 9 different designs with Ø10, Ø14 or Ø20 reinforcement in the air cure group
Figure 9. Relationship between electrical resistivity and Uniaxial Compressive Strength of 9 different designs unreinforced and reinforced cubic samples including Ø10, Ø14 or Ø20 reinforcement in water cure group
Figure 10. Relationship between electrical resistivity and Uniaxial Compressive Strength of 9 different designs reinforced cubic samples of including Ø10, Ø14 or Ø20 reinforcement in which air-cure group.
Figure 11. Relationship between electrical resistivity and Uniaxial Compressive Strength of 9 different designs unreinforced and reinforced cubic samples including Ø10, Ø14 or Ø20 reinforcement in which water and air cure groups
Figure 12. Comparison of the electrical resistivity values of reinforced cubes in the water and air cure
Figure 13. The relationship between the electrical resistivity and uniaxial compressive strength of reinforced cubes in water cure (a) and air cure (b)
Figure 14. Showing of the relationship between the electrical resistivity and uniaxial compressive strength of reinforced and unreinforced all cubes of water and air cured depending on reinforcement diameter.
Figure 15. Changes of the electrical resistivity depending on measurement direction of reinforced and unreinforced all cubes samples in water and air cured.

Table 1.

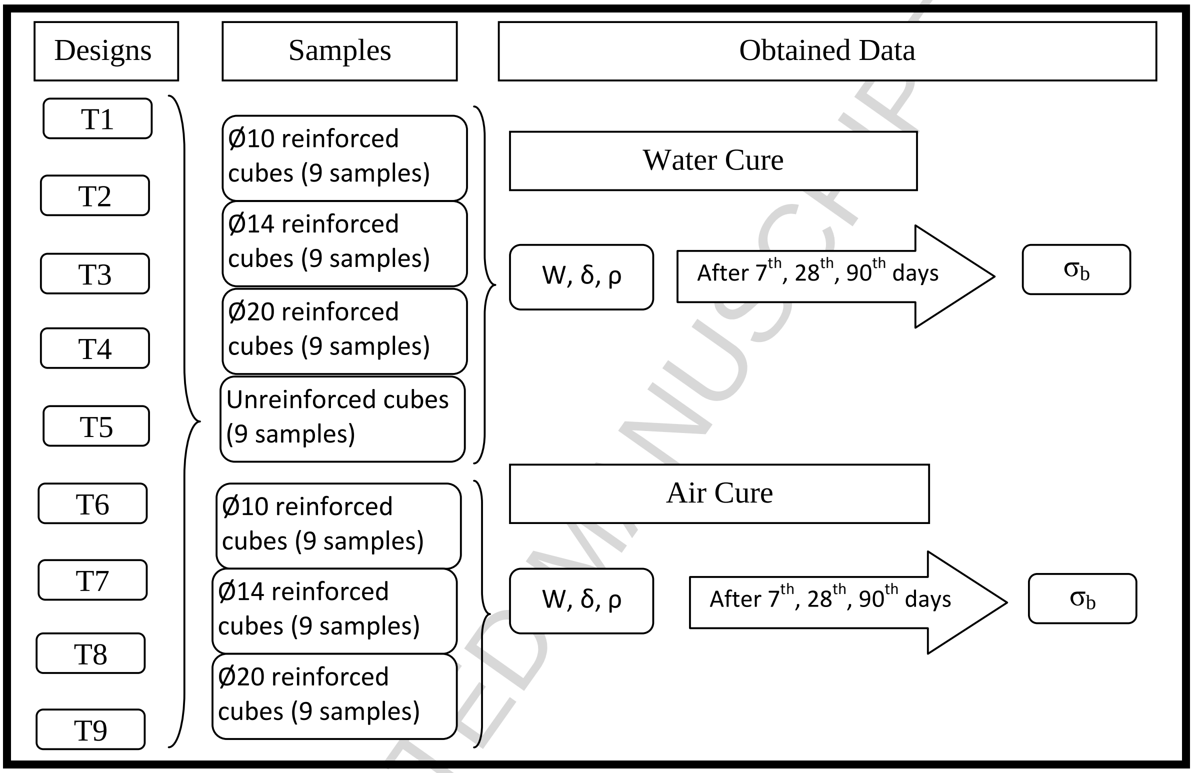

Designs
Samples
Obtained Data
T1
T2
T3
T4
T5
T6
T7
T8
T9
Ø10 reinforced cubes (9 samples)
Ø14 reinforced cubes (9 samples)
Ø20 reinforced cubes (9 samples)
Unreinforced cubes (9 samples)
Water Cure
W, δ, ρ
After 7th, 28th, 90th days
σb
Ø10 reinforced cubes (9 samples)
Ø14 reinforced cubes (9 samples)
Ø20 reinforced cubes (9 samples)
Air Cure
W, δ, ρ
After 7th, 28th, 90th days
σb

Table 2.

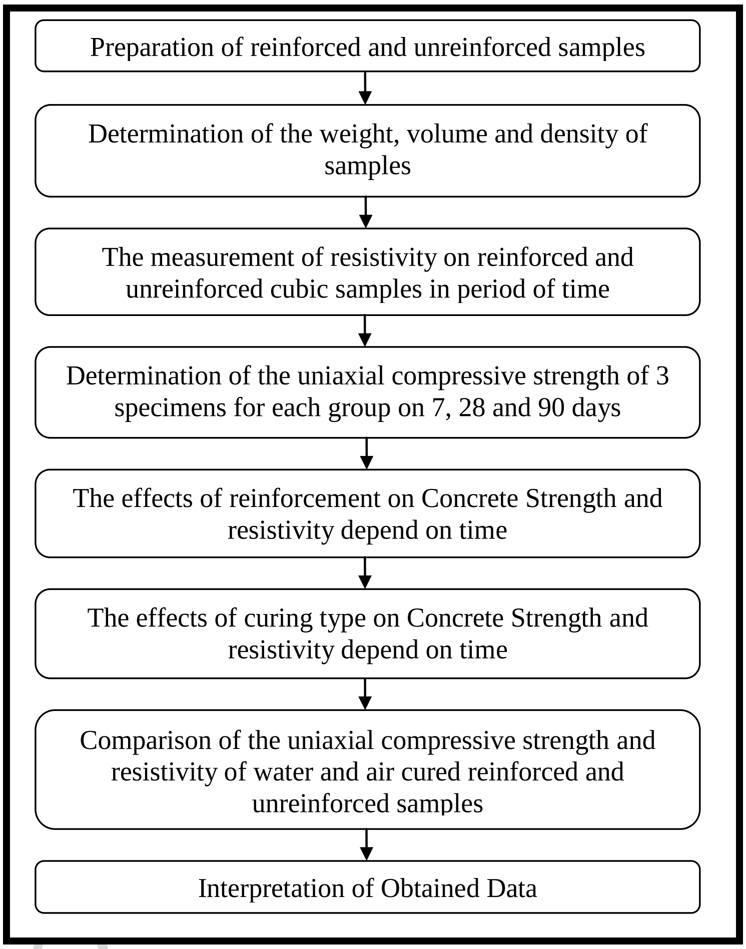

Preparation of reinforced and unreinforced samples
Determination of the weight, volume and density of samples
The measurement of resistivity on reinforced and unreinforced cubic samples in period of time
Determination of the uniaxial compressive strength of 3 specimens for each group on 7, 28 and 90 days
The effects of reinforcement on Concrete Strength and resistivity depend on time
The effects of curing type on Concrete Strength and resistivity depend on time
Comparison of the uniaxial compressive strength and resistivity of water and air cured reinforced and unreinforced samples
Interpretation of Obtained Data

Table 3.

		Water Cure						Air Cure					
Time (day)	Sample Type	Resistivity (kΩcm)			Strength (MPa)			Resistivity (kΩcm)			Strength (MPa)		
		min.	max.	mean	min.	max.	mean	min.	max.	mean	min.	max.	mean
7	D	4.70	12.90	9.01	2.70	63.50	38.19	-	-	-	-	-	-
	Ø10	4.50	12.50	8.81	4.00	56.00	36.36	18.00	47.40	26.48	4.80	67.70	41.88
	Ø14	4.50	11.50	8.39	4.30	56.20	36.03	19.00	42.05	25.62	4.90	60.10	39.98
	Ø20	4.30	11.50	8.20	4.80	60.00	36.20	19.78	34.64	24.62	5.10	58.20	37.74
28	D	5.20	14.60	9.80	4.00	65.30	41.27	-	-	-	-	-	-
	Ø10	4.70	12.70	9.27	4.50	58.90	39.27	17.00	48.00	25.95	5.10	67.40	43.41
	Ø14	4.70	12.70	8.96	4.60	61.70	39.37	18.51	41.90	25.30	5.30	62.40	41.39
	Ø20	4.80	12.70	8.83	5.30	64.90	39.40	17.85	37.00	24.14	5.90	59.00	39.10
41	D	5.50	14.50	10.21	-	-	-	-	-	-	-	-	-
	Ø10	5.20	13.00	9.47	-	-	-	18.70	58.74	30.19	-	-	-
	Ø14	5.10	12.60	9.19	-	-	-	15.90	56.19	30.29	-	-	-
	Ø20	5.10	11.70	8.64	-	-	-	15.60	53.44	29.15	-	-	-
56	D	5.70	16.50	11.42	-	-	-	-	-	-	-	-	-
	Ø10	5.50	15.10	10.57	-	-	-	20.20	56.76	29.95	-	-	-
	Ø14	5.20	14.70	10.23	-	-	-	16.20	51.94	28.25	-	-	-
	Ø20	5.30	12.90	9.36	-	-	-	15.80	47.48	27.17	-	-	-
65	D	5.80	16.90	11.71	-	-	-	-	-	-	-	-	-
	Ø10	5.60	15.50	10.83	-	-	-	20.50	48.18	31.37	-	-	-
	Ø14	5.40	15.20	10.33	-	-	-	16.40	51.06	32.21	-	-	-
	Ø20	5.40	13.80	9.47	-	-	-	15.30	47.98	30.66	-	-	-
72	D	5.90	16.40	11.67	-	-	-	-	-	-	-	-	-
	Ø10	5.90	14.80	10.73	-	-	-	20.80	50.00	31.26	-	-	-
	Ø14	5.70	14.70	10.33	-	-	-	17.00	43.33	30.10	-	-	-
	Ø20	5.70	13.10	9.49	-	-	-	16.10	50.51	30.18	-	-	-
90	D	6.00	15.40	10.90	4.60	64.30	43.06	-	-	-	-	-	-
	Ø10	5.00	14.50	10.21	5.10	63.50	42.83	17.94	40.73	24.45	4.60	62.80	41.27
	Ø14	5.10	13.40	10.00	5.30	65.80	42.02	17.55	39.31	24.22	5.20	60.10	39.97
	Ø20	5.50	13.10	9.61	5.50	70.00	41.51	18.19	35.00	23.24	5.30	56.70	38.06

Figure 1.


Cubic sample
Device of resistivity measurement
Value of Resistivity
10.6 kΩ cm
resipod
proceq

Figure 2.

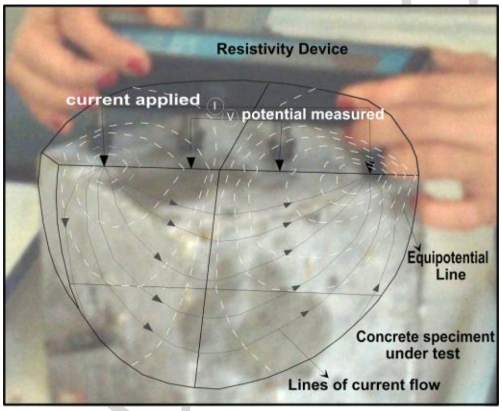
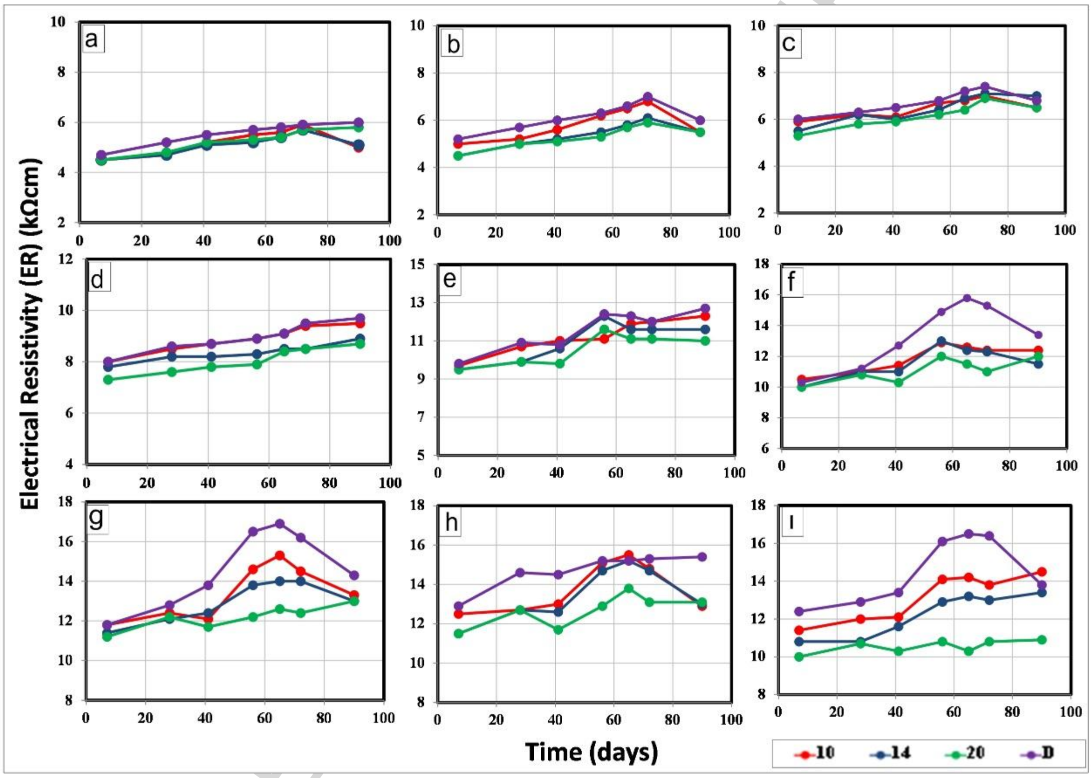

Resistivity Device
current applied
I
V
potential measured
Equipotential Line
Concrete speciment under test
Lines of current flow

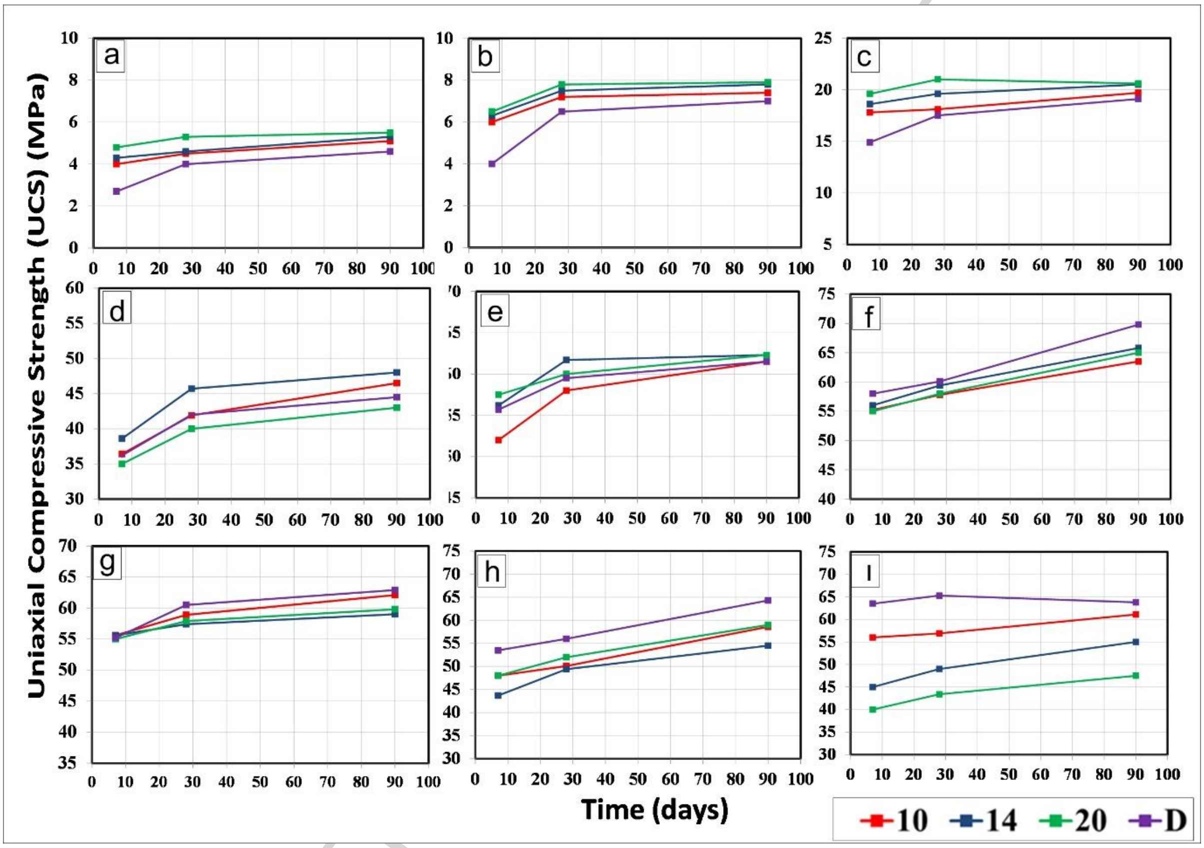
Figure 3.

Figure 4.



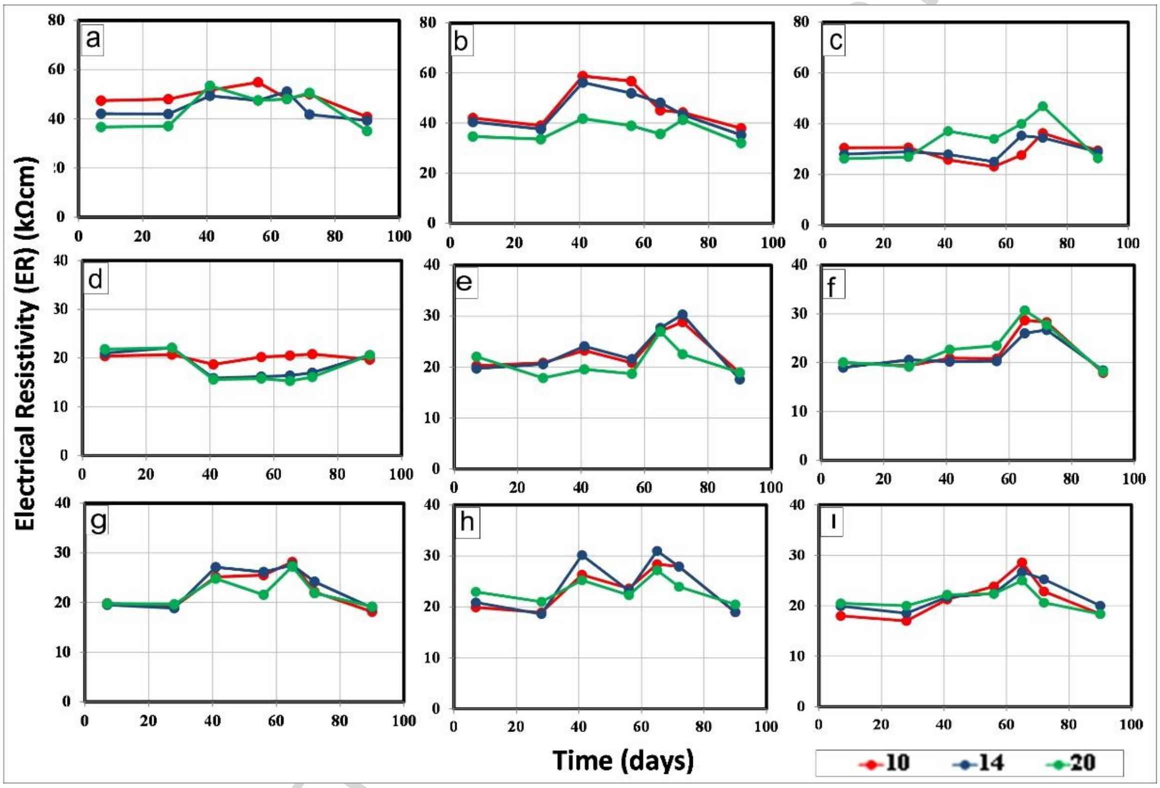
Electrical Resistivity (ER) (kΩcm)
Time (days)
a
b
c
d
e
f
g
h
i
10
14
20
D

Figure 5.



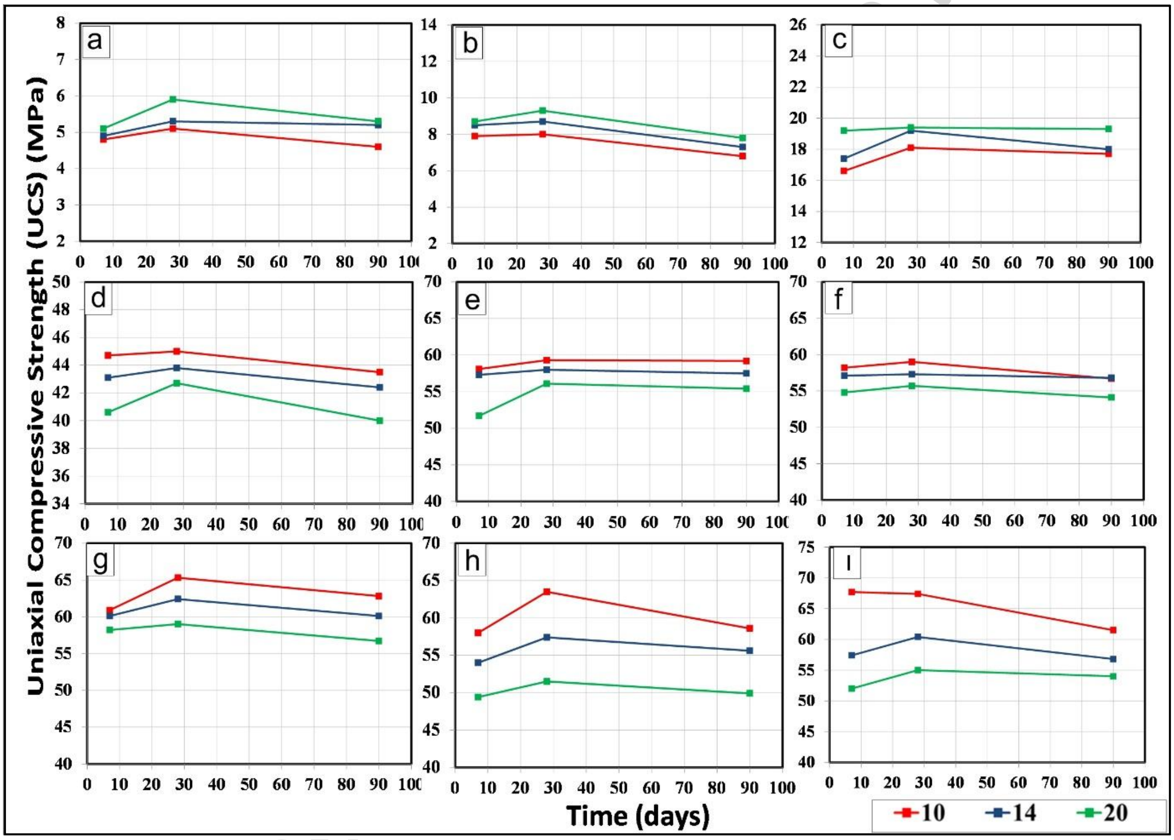
Uniaxial Compressive Strength (UCS) (MPa)
Time (days)
a
b
c
d
e
f
g
h
I
10
14
20
D

Figure 6.



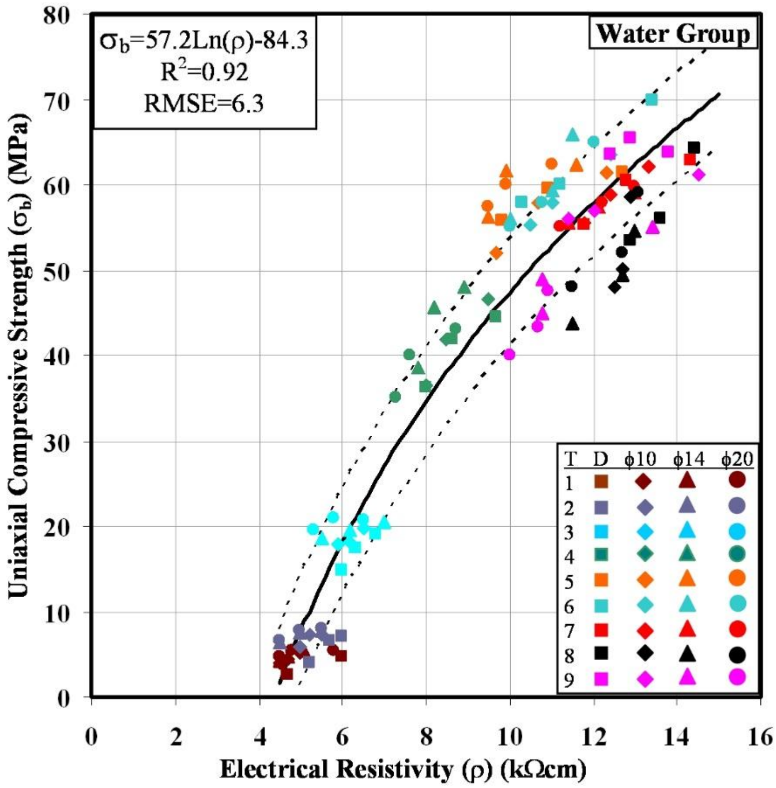
Electrical Resistivity (ER) (kΩcm)
Time (days)
a
b
c
d
e
f
g
h
i
10
14
20

Figure 7.



Uniaxial Compressive Strength (UCS) (MPa)
Time (days)
a
b
c
d
e
f
g
h
I
10
14
20

Figure 8.



σb=57.2Ln(ρ)-84.3
R²=0.92
RMSE=6.3
Water Group
T D ϕ10 ϕ14 ϕ20
1
2
3
4
5
6
7
8
9
Uniaxial Compressive Strength (σb) (MPa)
Electrical Resistivity (ρ) (kΩcm)
0
10
20
30
40
50
60
70
80
0
2
4
6
8
10
12
14
16

Figure 9.

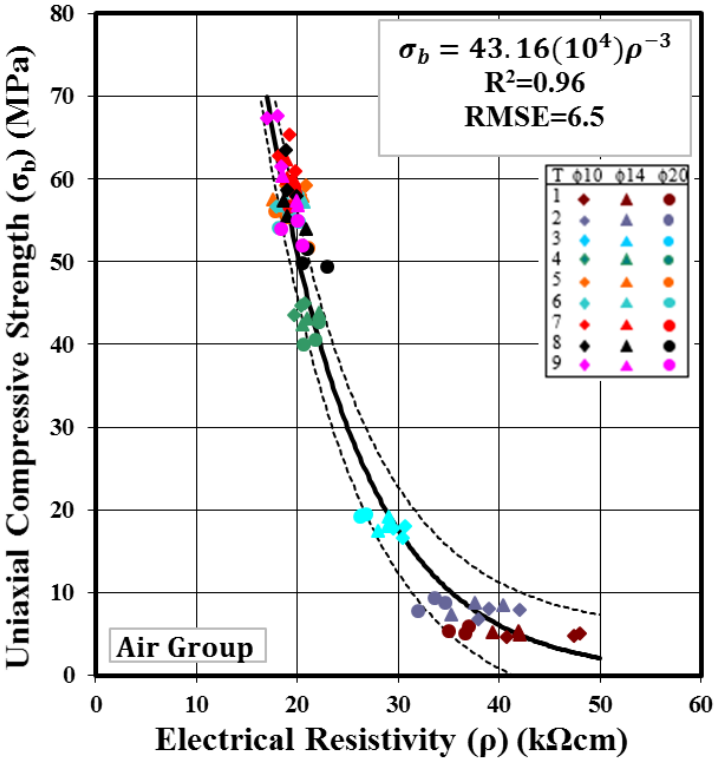
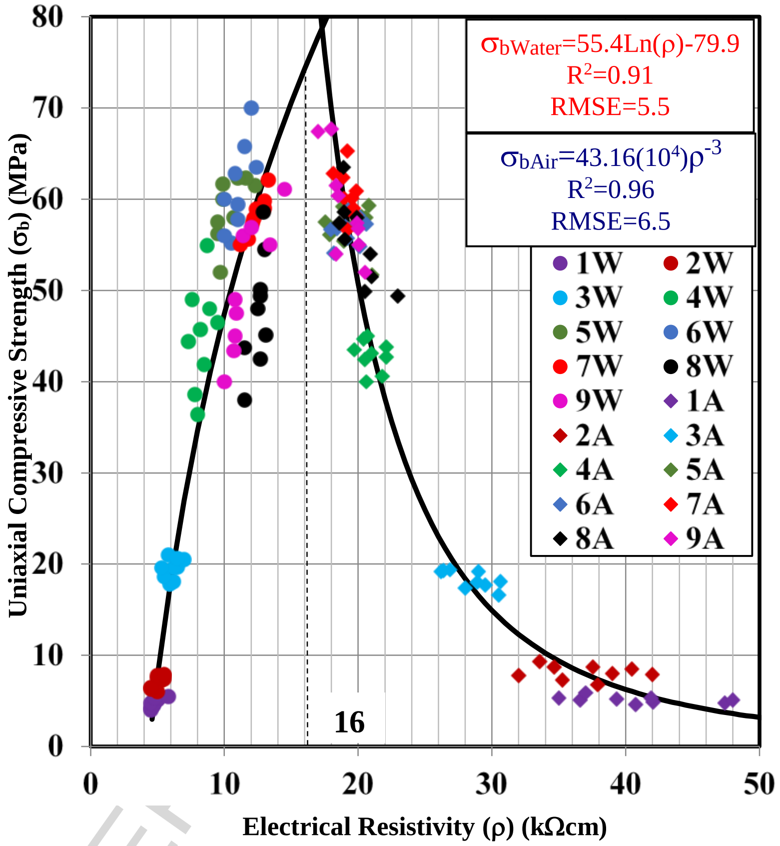
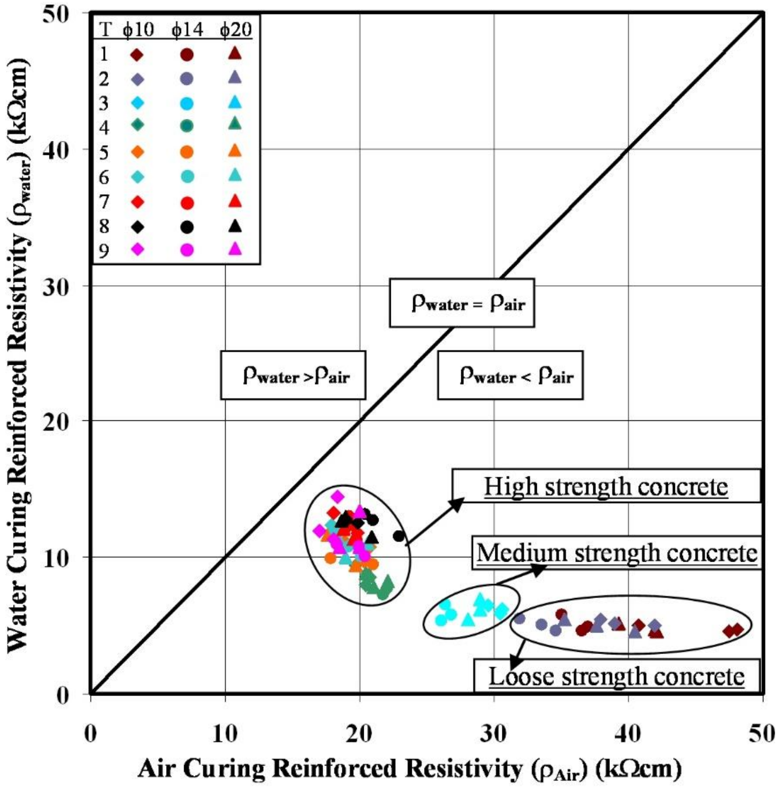

$\sigma_b = 43.16(10^4)\rho^{-3}$
R²=0.96
RMSE=6.5
T φ10 φ14 φ20
1
2
3
4
5
6
7
8
9
Air Group
Uniaxial Compressive Strength (σb) (MPa)
Electrical Resistivity (ρ) (kΩcm)
0
10
20
30
40
50
60
70
80

Figure 10



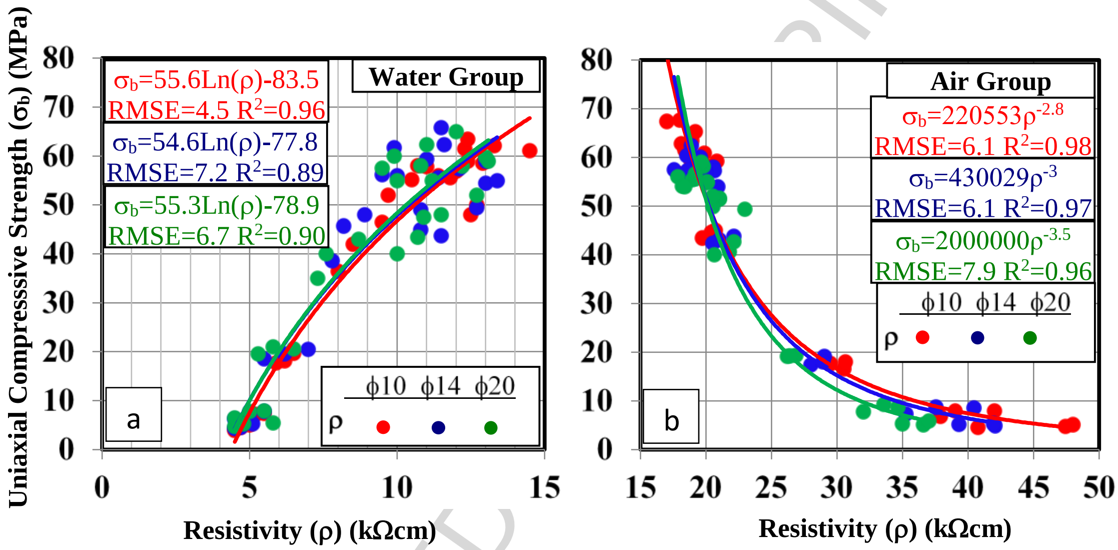
σbWater=55.4Ln(ρ)-79.9
R2=0.91
RMSE=5.5
σbAir=43.16(104)ρ-3
R2=0.96
RMSE=6.5
1W 2W 3W 4W 5W 6W 7W 8W 9W 1A 2A 3A 4A 5A 6A 7A 8A 9A
16
Uniaxial Compressive Strength (σb) (MPa)
Electrical Resistivity (ρ) (kΩcm)
0
10
20
30
40
50
60
70
80

Figure 11.



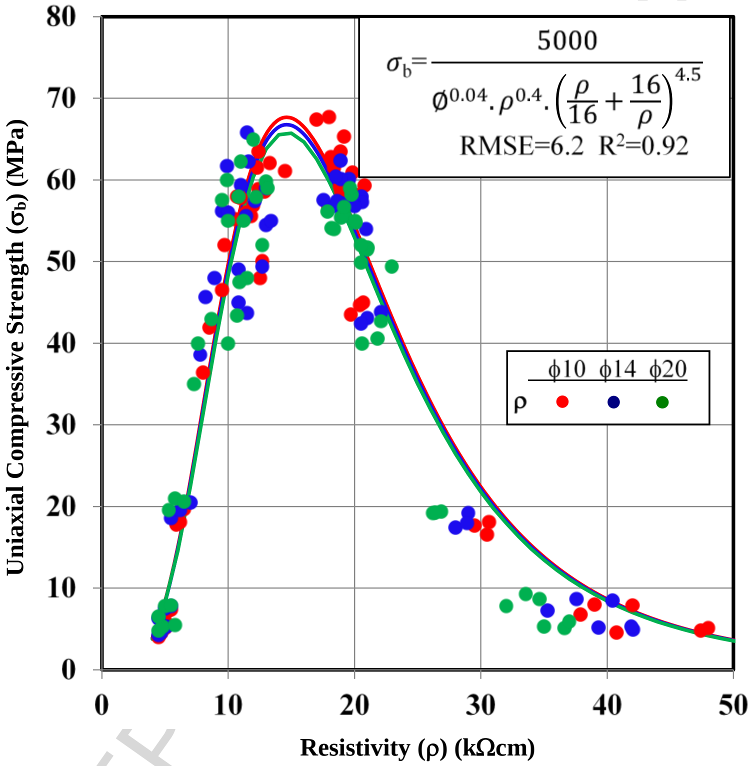
T ϕ10 ϕ14 ϕ20
1
2
3
4
5
6
7
8
9
ρwater = ρair
ρwater > ρair
ρwater < ρair
High strength concrete
Medium strength concrete
Loose strength concrete
0
10
20
30
40
50
Air Curing Reinforced Resistivity (ρAir) (kΩcm)
Water Curing Reinforced Resistivity (ρwater) (kΩcm)

Figure 12.



Uniaxial Compresssive Strength (σb) (MPa)
σb=55.6Ln(ρ)-83.5
RMSE=4.5 R2=0.96
σb=54.6Ln(ρ)-77.8
RMSE=7.2 R2=0.89
σb=55.3Ln(ρ)-78.9
RMSE=6.7 R2=0.90
Water Group
ϕ10 ϕ14 ϕ20
ρ
a
Resistivity (ρ) (kΩcm)
Air Group
σb=220553ρ-2.8
RMSE=6.1 R2=0.98
σb=430029ρ-3
RMSE=6.1 R2=0.97
σb=2000000ρ-3.5
RMSE=7.9 R2=0.96
ϕ10 ϕ14 ϕ20
ρ
b
Resistivity (ρ) (kΩcm)

Figure 13.



$\sigma_b = \frac{5000}{\emptyset^{0.04}.\rho^{0.4}.\left(\frac{\rho}{16}+\frac{16}{\rho}\right)^{4.5}}$
RMSE=6.2 R²=0.92
ϕ10 ϕ14 ϕ20
ρ
Uniaxial Compressive Strength (σb) (MPa)
Resistivity (ρ) (kΩcm)
0
10
20
30
40
50
60
70
80

Figure 14.

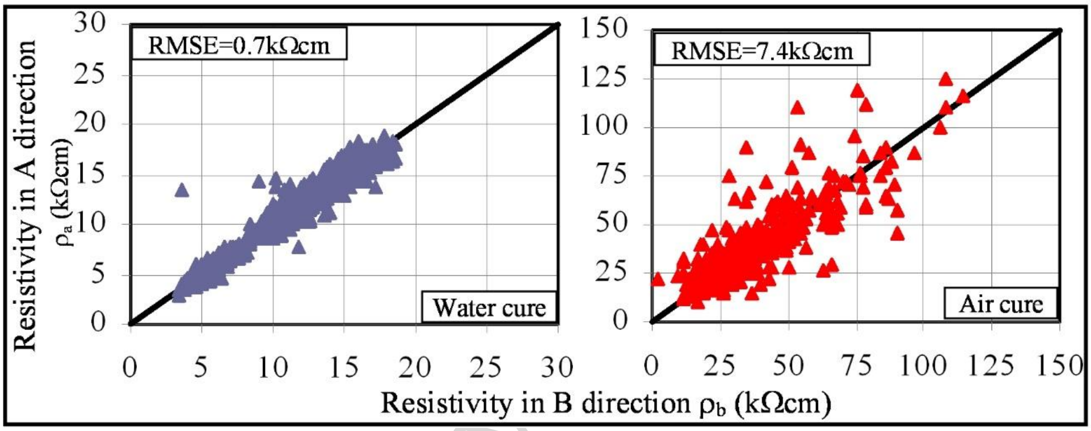

RMSE=0.7kΩcm
Water cure
RMSE=7.4kΩcm
Air cure
Resistivity in A direction ρa (kΩcm)
Resistivity in B direction ρb (kΩcm)
0
5
10
15
20
25
30
0
25
50
75
100
125
150

Figure 15.

Highlights

>567 samples in total with reinforced (10, 14 or 20mm reinforcement diameter) and unreinforced 9 different concrete designs were subjected to water and air curing during 90-days period. >UCS and apparent resistivity of samples were measured on certain days of the 90-days period. > The article emphasizes that can be predicted of the UCS values from the combined use of the apparent resistivity values of reinforced concrete in water and air cure and it determines to the effect of curing conditions on the resistivity values