Non-destructive electrical resistivity measurement technique: evaluation of concrete strengths

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ABSTRACT: The process of controlling concrete quality has proven to be a vital and essential procedure in concrete construction to ensure the quality of the constructed facility. The quality control procedures generally depend on the results of compressive strength testing for standard concrete specimens manufactured during the concrete construction process. The results of these specimens do not represent the whole sources of variations in the actual concrete strength because these samples are taken or extracted in the middle of the concrete construction process just before casting, compaction and curing which does not represent the actual condition in the real structure as stated by the ACI 214R-02 committee report. This fact calls for the need of a performance based quality control system that depends on the actual concrete strengths in the concrete structure under real construction conditions. Concrete electrical resistivity measurements are one of the promising techniques that can be used to evaluate concrete strength. This technique can be considered as a simple and low cost technique for evaluating the actual concrete quality during the construction process and also for actual inspection of the concrete structure.

This research aims to understand the relation between the concrete Surface Electrical Resistivity Measurements (SERM) and the different concrete strengths (such as compressive strength, tensile strength and flexural strength). Moreover, it is targeted to study and appraise the concrete SERM as a Non Destructive Test (NDT) for evaluation of the concrete strength and comparing it with other NDTs. These objectives are achieved through designing and conducting an extensive experimental program. The parameters involved in this research are water-to-cement ratio, age and the presence of silica fume as a replacement of cement content. Eight concrete mixes were designed and cast and more than 135 specimens were tested in compression, splitting tension and flexure. SERM were collected for theses samples at different ages using Wenner technique just before strength testing, and Schmidt rebound hammer was also used for comparison purposes.

The results of this study illustrated the sensitivity of the SERM to both age and water-to-cement ratio, while the effect of silica fume was less pronounced. It was shown that the higher the water-to-cement ratio for all the mixes, the lower the SERM, while age had the opposite effect. Moreover, relations between SERM and different concrete strengths were observed. In this research, linear statistical regression models were developed to represent the relation between the SERM and the different concrete strengths. Also the effect of the shape of the specimens on SERM was investigated.

1 INTRODUCTION

For several decades, concrete has been the dominant construction material for most construction projects. The reason for the popularity of concrete can be mainly summarized in its superior technical properties, economy, availability of its raw materials and manufacturing simplicity compared to other more complicated competitive construction materials. Concrete is also characterized by the variability in properties of its ingredients which has a major influence on its properties in general. Therefore, the selection of concrete-making materials and the uniformity of such raw materials have a great impact on concrete quality. Moreover, the manufacturing and construction processes and the maintenance of the concrete structures play an important role in the concrete quality affecting structure integrity and the life cycle of concrete structures.

It is often necessary to test concrete structures after the concrete has hardened to determine whether the structure is suitable for its intended purposes. The quality of concrete is mainly judged by its compressive strength directly affecting the load-bearing capacity and durability of concrete structures, but the compressive strength test is destructive and causes damage to the concrete therefore concrete testing is a challenging problem. Many engineers, who are concerned when they want to measure the quality and strength of a building because strength testing is destructive, are turning to non-destructive testing techniques.

Generally, during construction, the concrete quality control process is performed based on concrete samples taken from the concrete batches just before casting. The concrete strength and its variation in results extracted from these concrete samples can be an indicator for two general sources of variations. The first source is the changes and variations due to the raw material variations and also variations in the concrete manufacturing process which ACI 214R-02 committee report (ACI, 2002) calls "Batch-to-Batch Variation". The other source of variation reported by the same committee is "Within Test Variation" resulted from sampling, manufacturing, curing and testing of the concrete samples. The true strength of the concrete structure and its variations depends, in addition to the two pre-mentioned sources, on a third source of variation that can be called the "Construction Practice Variation" which takes place after extracting the concrete sample from the concrete batch. This shows that this method of quality control does not truly represent the concrete quality and another method representing performance-based quality control is needed to evaluate the concrete quality (Gjφrv 2003, Sengul & Gjφrv 2008, Ferreira & Jalali 2006, 2010).

The objective of this research is to evaluate the use of surface electrical resistivity measurements (SERM) as a non-destructive performance based quality control tool that can be used in concrete construction. This can serve as a quality control tool to assess the concrete strength at different ages, with different water to cement ratios and different ingredients. For this purpose, several parameters were studied: including the water to cement ratio, the concrete age and the presence of silica fume. For comparative reasons, other non-destructive measurements were taken for the concrete using a Schmidt rebound hammer tester in correspondence with the surface electrical resistivity measurements (SERM).

2 NON-DESTRUCTIVE TESTING

Concrete structures should often be tested after the concrete has hardened to determine whether the structure is suitable for its intended and designed purposes. These tests should preferably be done without any damage to the concrete and with no effect on the integrity of the concrete structure. The tests available for concrete inspection range from the completely non-destructive, where there is no damage to the concrete, through those where the concrete surface is slightly damaged, to partially destructive tests, such as core tests and pullout and pull off tests, where the surface has to be repaired after the test. Generally, non-destructive testing can be applied to both old and new structures. For new structures, the principal applications are likely to be for quality control or the resolution of doubts about the quality of materials or construction. The testing of existing structures is usually related to an assessment of structural integrity or adequacy. In either case, if destructive testing alone is used, for instance, by removing cores for compression testing, the cost of coring and testing may only allow a relatively small number of tests to be carried out on a large structure which may be misleading. Non-destructive testing can be used in those situations as a preliminary to subsequent coring (Malhotra & Carino 2004).

2.1 *Schmidt rebound hammer*

This widely known and used non-destructive technique depends essentially on concrete surface hardness by impacting the concrete surface with a given energy of impact and measuring the rebound. Schmidt rebound hammer generally consists of a spring controlled hammer that slides on a plunger. The hammer is pressed against the concrete and against the force of the spring until the end of its retraction. At this point the hammer is released to impact the concrete surface and then retracts with a pointer on a guided scale that represents the rebound number (Mehta & Monteiro 2006). The detailed procedure is fully described in ASTM C805 (ASTM, 2008) and a schematic diagram showing the rebound hammer is presented in Figure 1.

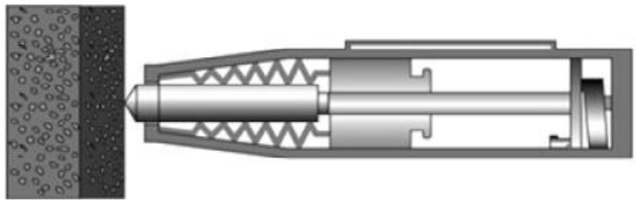

Figure 1. Schematic diagram for the Schmidt rebound hammer (ACI 228.1 R-03)

The rebound hammer is famous for getting quick and inexpensive results for checking the uniformity of hardened concrete using a simple technique (Malhotra & Carino 2004). The results of this method are known to be affected by different parameters such as the surface smoothness, the surface moisture content, the aggregate type, the degree of carbonation, the direction of the hammer during the test and the age and size of the specimen.

2.2 *Surface Electrical Resistivity Measurements (SERM)*

Variations in concrete electrical properties due to the effect of different concrete exterior or interior factors have been studied (Kazberuk & Jezierski 2005, Su et al. 2002) as the basis for understanding durability and in different non-destructive techniques. The properties include electrical resistance, dielectric constant, and polarization resistance. The conduction of electricity by moist concrete could be expected to be essentially electrolytic which depends on the evaporable water content of concrete that varies with water-to-cement ratio, the degree of hydration, and the degree of saturation. This water contains ions, primarily Na^+, K^+, Ca^{2+}, SO_4^{2-}, and OH^-, whose concentrations vary with time which also greatly affect the concrete conductivity or resistivity (Malhotra & Carino 2004).

The resistivity of concrete is an important parameter in the corrosion of reinforced concrete structures as high-resistivity concrete has little possibility of developing reinforcement corrosion (Andrade et al. 2009, Morris et al. 2004, Millard et al. 1989). Concrete resistivity measurements have also been explored lately in damage detection for concrete structures (Lataste et al. 2003).

SERM can be collected using several different techniques, however the most famous arrangement is the four point probe called the "Wenner Technique" which is shown in Figure 2. The Wenner Method uses a four-point probe in contact with the measured material where a low frequency alternating electrical current is passed between the two outer electrodes whilst the voltage drop between the inner electrodes is measured as shown in Figure 2.

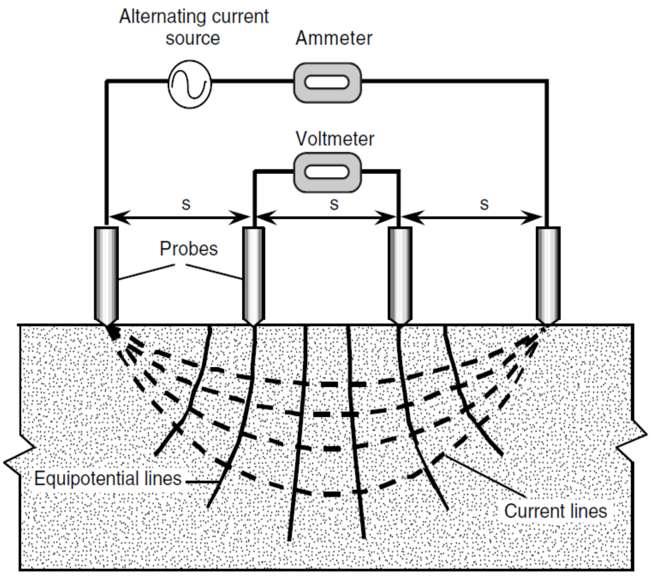

Figure 2. Four-probe resistivity test (Malhotra & Carino 2004).

The equation for calculating the Surface Electrical Resistivity (ER) from the Electrical Resistance (R) is shown as follow:

$$ER = 2\pi s \times R \qquad (1)$$

Where

s distance between probes (as shown in Figure 2)

R = electric resistance = $\Delta V / I$

ΔV voltage drop between the inner electrodes

I electrical current

3 EXPERIMENTAL DETAILS

This research aims to study the surface electrical resistivity measurements (SERM) conducted on concrete surfaces using the Wenner testing method. The relationships between these measurements and different measured strengths (compression, splitting tensile and flexural) at different ages are investigated in this research also. Another widely used non-destructive concrete testing technique, Schmidt Rebound Hammer, is used in this study for comparison purposes.

To achieve the pre-mentioned objectives, a comprehensive experimental program was planned and conducted and the results will be outlined in this study. Among the main parameters involved in this research is the water-to-cement ratio which ranged from 0.25 to 0.55 to cover a wide range of the used concrete while the slump was kept in the range of 10 to 20 cm by using superplasticizer. The other parameter used in this study is the presence of silica fume as a replacement of cement content of 0 and 10 percent. A total of 8 mixes were designed and cast in this study. For mix design purposes, the following assumptions were made: the cement content (or the binder content [cement + Silica fume] for mixes containing silica fume) was kept constant at 450 kg/m^3, air content = 2%, the ratio of coarse aggregate to fine aggregate was kept = 2 and the used water to cement ratios were 0.25, 0.35, 0.45 and 0.55. Based on these assumptions, the absolute volume method is used to assess the mix proportions and the quantities for each component. The details for all of the 8 mixes are shown in Table 1. In this study, the coarse aggregate used was crushed pink limestone with a nominal maximum aggregate size of 20 mm while clean sand was used and both aggregates satisfied the requirements of the Egyptian specifications. The cement used was Portland cement CEM I which satisfies Egyptian specifications.

For each mix, the slump was measured immediately after pouring the concrete and a total of 17 specimens (9 cubes 100*100*100 mm, 4 cylinders [D*L] 75*150 mm and 4 beams 75*75*250 mm) were cast then tested after hardening. All the specimens were cured in a lime bath until the testing age. The concrete cubes were tested in compression at ages 3, 7 and 28 days (3 cubes at each age) while the cylinders and beams were tested in splitting tension and flexure respectively at ages of 7 and 28 days (2 specimens of each shape at each age).

All the concrete specimens were tested (while completely saturated with water) just after removing them from water using two non-destructive techniques (Schmidt rebound hammer and Surface electrical resistivity measurements SERM) just before destructive testing was conducted. The instrument used for collecting the SERM was a battery operated digital earth resistance tester model F – 366 which is shown in Figure 3. This apparatus was adapted to directly measure resistance in Ohm. Four different ranges or scales (20, 200, 2000 and 20,000 Ohm) of electrical resistance measurements were available to assure high accuracy when measuring low and high electrical resistance. The accuracy of this tester was ±1% of the maximum value in the range being used. It was calibrated by the Atomic Energy Authority in Alexandria before use and it was found that the error did not exceed ±0.2%. An equal distance between the four brass probes of 25 mm was set for all the measurements on all of the specimens.

Table 1. Concrete mix design

Mix No.	Cement (Kg/m^3)	Silica Fume (Kg/m^3)	Water (Kg/m^3)	W/C	Coarse Agg. (Kg/m^3)	Fine Agg. (Kg/m^3)
1	450	0	247.5	0.55	1073.4	536.7
2	405	45	247.5	0.55	1073.4	536.7
3	450	0	202.5	0.45	1155.4	577.7
4	405	45	202.5	0.45	1155.4	577.7
5	450	0	157.5	0.35	1237.3	618.7
6	405	45	157.5	0.35	1237.3	618.7
7	450	0	112.5	0.25	1319.3	659.6
8	405	45	112.5	0.25	1319.3	659.6

Figure 3. The earth resistance tester used

For electrical resistance measurements, the measuring process was performed differently for each specimen. The measurements were conducted on the four surfaces parallel to the direction of casting for each specimen, and then these readings were averaged. After that each concrete cube specimen was tested in compression and the average of the three specimens for each age was determined. For the cylinder specimens, each cylinder was measured four times using the Wenner technique on two perpendicular planes along its side and parallel to its main axis. A total of 8 readings for each age were gathered then averaged, after that the cylinders were tested in splitting tension. For the beam specimens, the specimens were measured along the two surfaces parallel to the casting direction. Four readings were gathered for each age and averaged then the two beam specimens were tested in flexure using a simple beam with a three-point loading technique and a span of 225 mm.

The concrete specimens were tested also using a Schmidt Rebound Hammer – shown in Figure 4 - along the same surfaces used for measuring the electrical resistivity. For each specimen, 12 measurements were collected and the readings were averaged for each age and each type of specimen. For comparison purposes, all the specimens were kept completely saturated during all the destructive and non-destructive testing process.

Figure 4. The used Schmidt rebound hammer tester

4 RESULTS AND DISCUSSIONS

In order to investigate the electrical resistivity measurements as a performance-based quality control non-destructive tool for the assessment and evaluation of concrete strengths such as compressive strength, splitting tensile strength and flexural strength for different concrete mixes with different parameters an objective was set to study the effect of age and water-to-cement ratio on the different strengths and to compare this effect with the effect on the electrical resistivity measurements and other NDT. Then, the relationship between the different strengths and the surface electrical resistance measurements (SERM) were investigated to model this relationship. Also, the effect of the specimen shape and type of loading on electrical resistivity was investigated.

4.1 *Effect of water-to-cement ratio*

The water-to-cement ratio is one of the main parameters that affect the properties of concrete and especially the different concrete strengths due to its effect on porosity and voids of the concrete microstructure. This means that it is important for any method for non-destructive testing to be sensitive to this factor to truly represent the concrete strength. The effect of water-to-cement ratio on cube compressive strength for different ages and for mixes containing only Portland cement and mixes containing 10 percent replacement of silica fume is presented in Figure 5-a. This figure shows the usual conclusions as to the harmful and adverse effect of increasing water to cement ratio on the concrete compressive strength, the increase in the compressive strength with age and a slight increase in the compressive strength due to the presence of silica fume. These effects are also similarly demonstrated for other concrete strengths such as the concrete splitting tensile strength and the flexural strength as shown in Figures 5-b and 5-c, respectively.

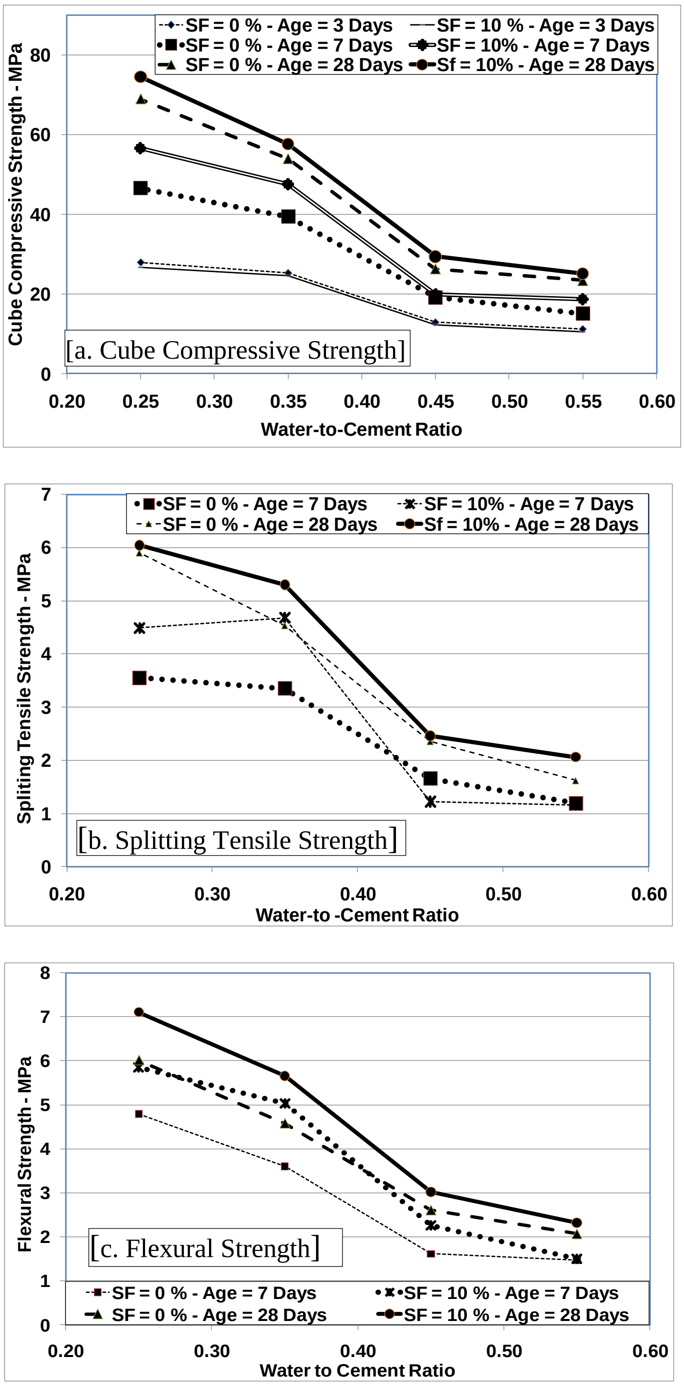

Figure 5. Effect of w/c ratio on concrete strengths (a. Cube strength - b. Splitting tensile strength - c. Flexural strength) at different ages. Silica fume replacement 0 &10 % by mass

Figure 6 shows the results of the resistivity measurements performed on the saturated concrete cubes just before conducting the compressive strength test. This figure presents the effect of water-to-cement ratio on electrical resistivity at different ages and with silica fume replacement of 0 and 10 % by weight. From this figure, it can be seen that increasing the water to cement ratio resulted in a reduction in the electrical resistivity of the concrete measured using the four point Wenner test method. As the concrete is a porous material and as the electric current is mainly transferred inside the concrete through the movement of the ions dissolved in the pores liquid, therefore the SERM is largely affected by the pore structure, porosity and the pore size distribution. Consequently, the reduction in SERM accompanied with the increase in water to cement ratio can be attributed to the increase in the porosity of the concrete leading to increase in the concrete conductivity. It was also observed from Figure 6 that for the mixes containing silica fume, the presence of the silica fume caused a slight increase in the concrete SERM compared with those concrete mixes with no silica fume. This can also be attributed to the pozzolanic effect of the silica fume represented in reducing the concrete porosity by plugging the pores and the enhancement of the pore size distribution leading to a reduction in the concrete conductivity and increase in SERM.

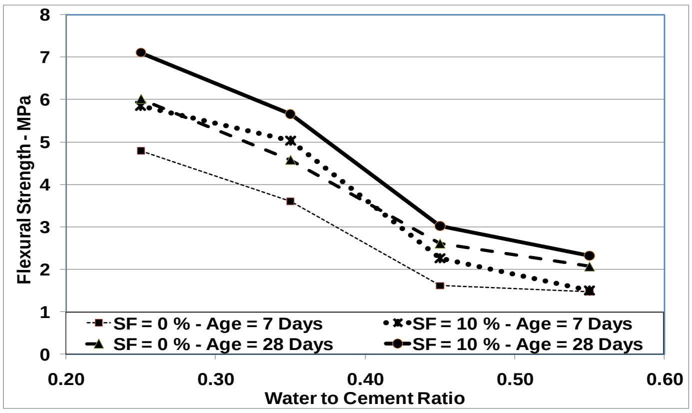

Figure 6. Effect of water-to-cement ratio on electrical resistivity at different ages with silica fume replacement of 0 and 10 % by mass

Schmidt hammer as a popular technique for concrete non-destructive testing is used in this study to compare its results with the SERM technique. The results for the rebound number taken for the concrete cubes just before testing in compression test are presented in Figure 7. This figure demonstrates the effect of the water to cement ratio on the rebound number where the increase in the water to cement ratio resulted in a reduction in the rebound number as stated in many references (Mehta & Monteiro 2006, Malhotra & Carino 2004). However, the significant increase in the water to cement ratio (from 0.25 to

0.55) did not show a considerable change in the Schmidt hammer rebound number as shown in Figure 7. Also the presence of silica fume did not show any noticeable or consistent change for the Schmidt rebound number results at any water to cement ratio. Based on the previous data, it can be seen that the SERM results were more significantly affected with two important parameters affecting the concrete strengths than the Schmidt hammer rebound number results. So, it can be concluded that the SERM technique is more sensitive to the parameters affecting the concrete strengths.

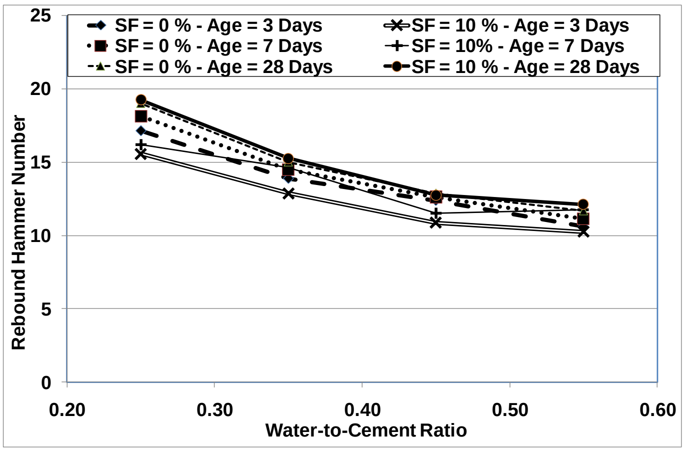

Figure 7. Effect of water-to-cement ratio on Schmidt hammer rebound number at different ages with silica fume replacement of 0 and 10 % by mass

4.2 *Effect of age on surface electrical resistivity measurements of concrete*

The concrete age is one of the main factors affecting concrete strength due to the hydration of the Portland cement resulting in a hydrated cement that has a larger volume which leads to plugging of the concrete pores and reducing the concrete voids. But this fact can also affect the SERM results where by plugging the concrete pores and reducing the concrete internal voids, the ability of the pore solution to carry or conduct the electrical current is significantly reduced. This effect is presented in Figure 8 which shows the effect of age on the SERM results for concrete cubes made with different water to cement ratio. From Figure 8, it can be concluded that the increase in concrete age resulted in an increase in the SERM for all the mixes with different water to cement ratios and for mixes with 10% silica fume replacement.

It can also be seen that the rate of the increase in the SERM is reduced with time as the increase in the SERM from 3 to 7 days age is higher than the increase in the SERM from 7 to 28 days as shown in Figure 8. This shows how much the SERM depends on the hydration rate which starts fast at concrete early age and then slows down with age. On the other hand, the results of the effect of age on the Schmidt rebound hammer, which are presented in Figure 9, show a slight change in the rebound number due to the change in the concrete age is taking place. Consequently, it can be seen that SERM can be an effective method to capture the behavior of the concrete strengths with time.

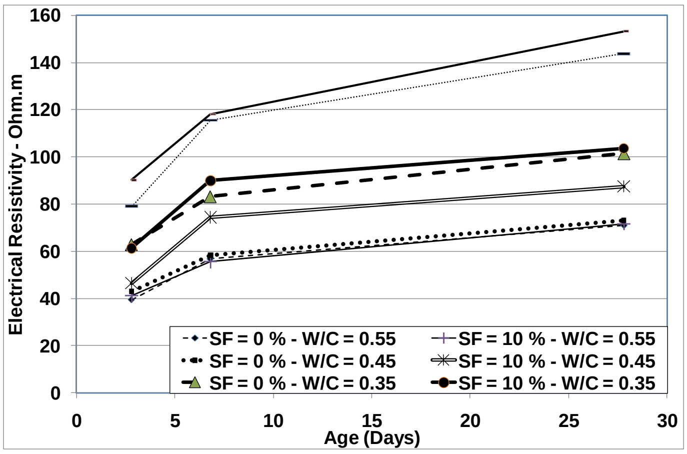

Figure 8. Effect of sge on electrical resistance for cubes made with different water-to-cement ratio

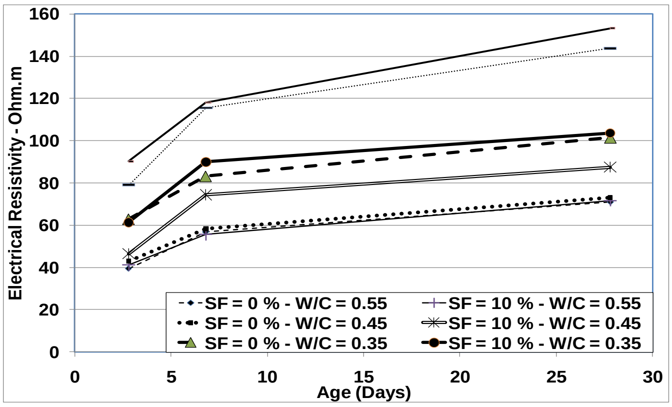

Figure 9. Effect of age on Schmidt hammer rebound number for cubes made with different water-to-cement ratio

4.3 *Relation between the strengths and Surface Electrical Resistivity Measurements (SERM)*

Although it was shown before that the SERM results are more sensitive to the main parameters affecting the concrete strengths such as water to cement ratio, age and presence of silica fume, the main challenge is still the relationship between the concrete strength and the SERM. The results of concrete cube compressive strength against SERM results are presented in Figure 10 for mixes with different water to cement ratios at different ages. From this figure it can be noticed that a linear relation between cube compressive strength and SERM can be established by linear regression analysis. This relationship is as follows:

$$f_c = 0.59 * ER - 14.69 \qquad (2)$$

Where f_c is the cube compressive strength and ER is the measured surface electrical resistivity for the same cube specimen

As the coefficient of determination for this model $R^2 = 0.91$, this means that the proposed model will show an accurate prediction for the compressive strength based on the SERM results for these specimens.

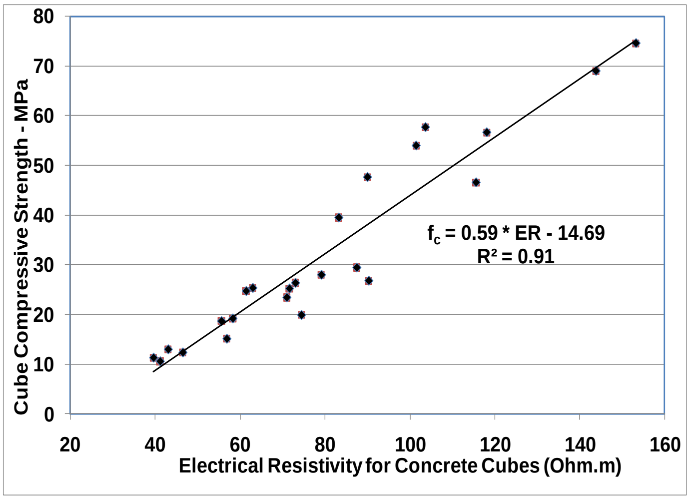

Figure 10. Relationship between cube compressive strength and electrical resistivity for cubes at different ages and water-to-cement ratios.

On the other hand, Schmidt rebound number results were collected for the same concrete cubes after collecting the SERM results then the compression test was performed immediately. The results of the cube compressive strength against the rebound number are presented in Figure 11 for different concrete mixes at different ages. From this figure it can be seen that a correlation between these two variables can exist and a linear regression model is proposed as shown in the figure. However, the coefficient of determination R^2 calculated for this model = 0.746 which is much lower than the one for the SERM data with the cube compressive strength. This means that the SERM results are more accurate in predicting the cube compressive strength than Schmidt rebound number. Moreover, it can be noticed that the value of coefficient of the parameter ER in the SERM model (which is 0.59) is much lower than the coefficient of the parameter RN (Rebound number) in the rebound number model (which is 6.134). This shows that the SERM model is much less sensitive to the prediction errors of the cube compressive strength than the rebound number because a change or error of the SERM by a unit will only cause a change or error in the cube compressive strength by 0.59 MPa, while the change or error of the rebound number by a unit will result in a change or error of the cube compressive strength by 6.134 MPa. This means that in case of a small error of 1 unit - for example - the error in predicting the cube compressive strength will be much lower in case of using the SERM technique than the Schmidt hammer technique.

Other models are proposed for the relation between the cylindrical splitting tensile strength vs. SERM and the flexural strength vs. SERM as shown in Figures 12 and 13. From these figures it can be noticed that a good correlation between the concrete splitting tensile and flexural strengths and SERM exists.

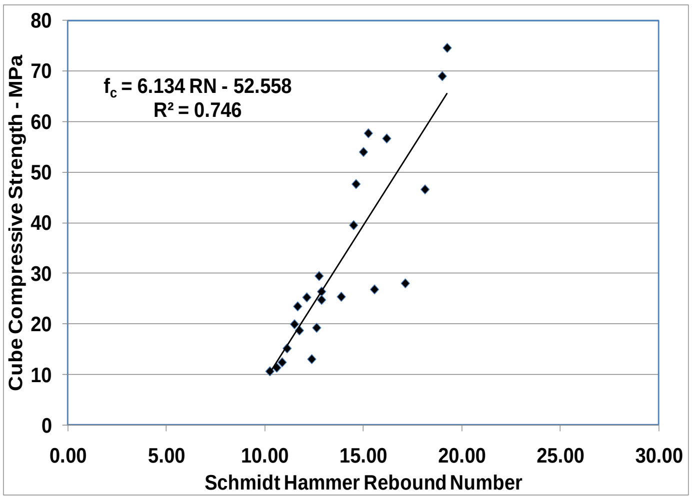

Figure 11. Relationship between cube compressive strength and Schmidt hammer rebound number for cubes at different ages and water-to-cement ratios.

The following linear regression models are proposed for the prediction of these concrete strengths:

For the prediction of concrete splitting tensile strength

$$f_{cy} = 0.054 * ER - 3.01 \quad (3)$$

The coefficient of determination for this model $R^2 = 0.92$

Where

f_{cy} is the cylindrical splitting tensile strength and

ER is the measured surface electrical resistivity for the same cylinder specimen

For the prediction of concrete flexural strength

$$f_b = 0.055 * ER - 1.314 \quad (4)$$

The coefficient of determination for this model $R^2 = 0.778$

Where

f_b is the flexural strength and

ER is the measured surface electrical resistivity for the same beam specimen

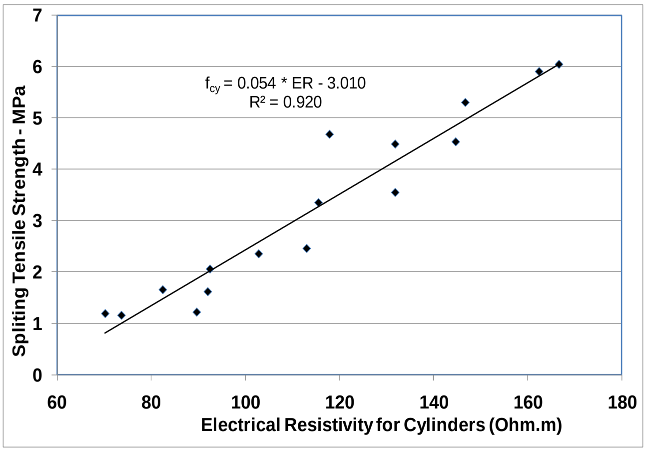

Figure 12. Relationship between splitting tensile strength and electrical resistance for cylinders at different ages and water-to-cement ratios

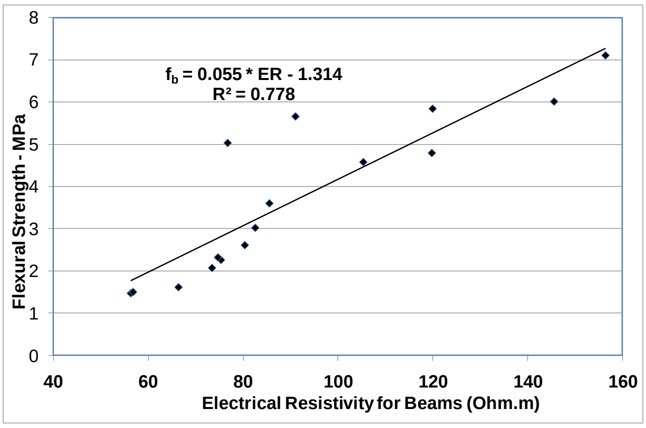

Figure 13. Relationship between flexural strength (using simple beam third-point loading) and electrical resistance for beams at different ages and water-to-cement ratios

4.4 *Effect of specimen shape on SERM*

To evaluate the effect of the concrete specimen shape on the SERM, two plots for the SERM results for the different specimen shapes used (Cubes, Cylinders and Beams) were constructed as shown in Figures 14 and 15. In Figure 14 the relations between SERM for concrete cubes as a vertical axis and SERM for the concrete cylinder and beam shaped specimens as a horizontal axis are plotted. Moreover, a linear regression model was proposed based on the available data to evaluate the effect of the specimen shape on SERM. From this figure it can be seen that the ratio between the SERM for the specimens with cubical and beam shapes is almost 1 which means that these results are almost equal with a coefficient of determination of 0.9834. On the other hand, the ratio between SERM for the specimens with cubical and cylindrical shaped is 0.7817 which is very close to the same ratio between SERM for beam and cylindrical shaped specimens (0.791) as shown in Figure 15. This means that the change of the shape from a cube to beam shape did not show significant effect on SERM while the change of the shape from cube or beam to cylinder showed an increase in SERM of around 25%.

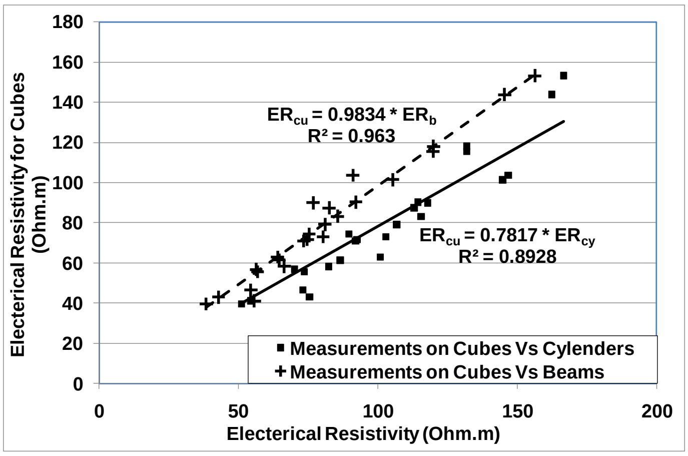

Figure 14. Relationship between electrical resistance measurements for cubes and electrical resistance measurements for cylinders and beams at different ages and water-to-cement ratios

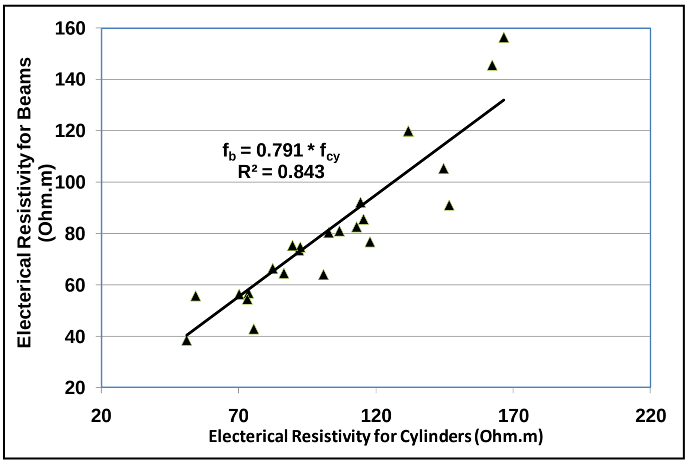

Figure 15. Relationship between electrical resistance measurements for beams and electrical resistance measurements for cylinders at different ages and water-to-cement ratios

5 SUMMARY AND CONCLUSIONS

During the last decades the construction industry has become more and more complicated and as good control over all the aspects of the construction projects is becoming more difficult than ever, the need for a concrete performance based quality control tool is growing. Moreover, the quality control process using the results of the compression test for specimens collected at the construction site does not reflect the real conditions of the concrete structure itself. In this research a comprehensive experimental program was conducted aiming to evaluate the use of SERM as a Non destructive technique to evaluate the different concrete strengths. Based on the results of this study the following conclusions can be claimed:

- The Surface Electrical Resistivity Measurements (SERM) technique used for concrete specimens is sensitive to the change in different parameters, studied in this research, such as water to cement ratio and concrete age, which influence the concrete strengths.

- The SERM results seem to be more sensitive to the above mentioned parameters than the Schmidt rebound number technique as shown in this study.
- A linear relation between the cube compressive strength and SERM results can exist. Moreover, a linear regression model that relate the cube compressive strength and SERM results is proposed in this study and is proven to be more sensitive than the one for Schmidt rebound number technique which was suggested in this study also.
- Similar linear regression models were proposed in this study to relate the SERM results with the splitting tensile strength and the flexural strength.
- The change in the specimen shape from cube to beam showed very little effect on the SERM results, however the SERM results for the cube and beam shaped specimens showed a lower value (around 80 %) than the cylindrical shaped specimens.

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