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An Experimental Study of Concrete Resistivity and the Effects of Electrode Configuration and Current Frequency on Measurement

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ABSTRACT

Electrical resistivity, a measurable parameter of the state of concrete, plays an important role in the assessment of reinforced concrete structures. An experimental study using two-electrode method has been conducted to evaluate the resistivity of Portland cement concrete. Internal and external electrodes were varied in order to understand effect of the electrodes configuration, where carbon fibre (CF) sheets were employed as the internal electrodes and CF and copper sheets were used as external electrodes. Furthermore, frequency of applied current was varied from low to high, to identify the most suitable frequency that can be utilized for stable and reliable results. Optimised internal electrodes configuration and the current frequency of 10,000 Hz were used to measure the resistivity on a series of concrete cubes, which were made using three different water to cement ratios and four different chloride contents.

Keywords: Concrete; electrical resistivity; two-electrode test method; carbon fibre; chloride.

1.0 INTRODUCTION

The electrical resistivity of concrete is an important parameter used to describe the durability of concrete structures and the risk of reinforcement corrosion (Bertolini *et al*., 2013, Morris *et al*., 2004, Hornbostel *et al*., 2013, Alonso *et al*., 1988). Furthermore, this property is essential for the design of electrochemical repair systems and monitoring the effectiveness of repairs. Corrosion rate is controlled by the ease with which ions can pass through the concrete from cathodic to anodic regions. Hence a large potential gradient associated with a low concrete resistivity will normally result in high corrosion rates. The resistivity of concrete may have values from tens to thousands of Ω.m. This is a function of the water content in the concrete, the type of cement used, the water to cement (w/c) ratio, the presence of chloride ion and the state of carbonation of concrete (Bertolini *et al*., 2013, Polder, 2001).

The most commonly used technique for in-situ testing is the Wenner 4-probe technique (Morris *et al*., 1996, Stanish *et al*., 1997, Layssi *et al*., 2015). The probes are placed on the surface of the test concrete and an alternating current passed between the outer two electrodes while voltage across the inner two is recorded. One of the drawbacks of this technique is that the conduction paths may not be accurately known.

More accurate resistivity values are obtained using external plate electrodes enabling the current to traverse the full area of the specimen. In this method, steel plates are placed to two parallel faces of a concrete cube or cylinder. Wet cloths are placed between the external electrodes and concrete surfaces for good electrical contact (Bertolini *et al*., 2013, Polder, 2001, Newlands *et al*., 2008, Spragg *et al*., 2011, Sengul, 2014, Van Noort *et al*., 2016). Nevertheless, an accurate reading can be a difficult due to the contact between the electrode and the concrete, particularly when measurements are employed on unsaturated specimens (Villagrán Zaccardi and Di Maio, 2014). The most direct and reliable mode of contact is embed electrodes into the fresh concrete. Then resistivity measurements can be performed on the concrete specimen at various moisture states without disrupting the moisture content of the specimen (Whiting and Nagi, 2003, Villagrán Zaccardi and Di Maio, 2014). Electrodes can be of various types. Brass is the most commonly used material, but steel is also used. They can be meshes or plates. In the case of embedded electrodes, wires or thin rods normally are used. In these cases, however, the flow path may not be defined well enough to calculate a true resistivity (Whiting and Nagi, 2003).

Either direct current (DC) or alternating current (AC) can be applied to determine the electrical resistivity of concrete according to Monfore (1968). However, AC is preferred as it is generally acknowledged that measurement of resistivity using DC polarises the electrodes (Stanish *et al*., 1997). Application of a DC voltage across a concrete specimen causes current flow, mostly carried by ions in the concrete pore water and electrochemical reactions occur at the electrodes (Hansson and Hansson, 1983). Such reactions produce polarization which, in turn, causes a decreased in the measured voltage (Stanish *et al*., 1997). This introduces uncertainty in the electrical resistivity measurement across the sample. In order to mitigate the effects of polarisation, it is suggested that AC is applied at the electrodes (Chacko *et al*., 2007, Layssi *et al*., 2015).

Previous researches have suggested the use of both low frequency, such as 60 Hz (Chacko *et al*., 2007), 107 Hz (Osterminski *et al*., 2012), 128 Hz (Newlands *et al*., 2008) and high frequency, such as 1000 Hz (Whittington *et al*., 1981) and 7500 Hz (Banthia *et al*., 1992). Thus, it is hard to define a specific optimal frequency due to the variation of the conditions of concrete. The applied voltage during resistivity measurements should be low to avoid heating of the concrete and usually in the range of 10 V or lower (Streicher and Alexander, 1995), and is only applied for short times.

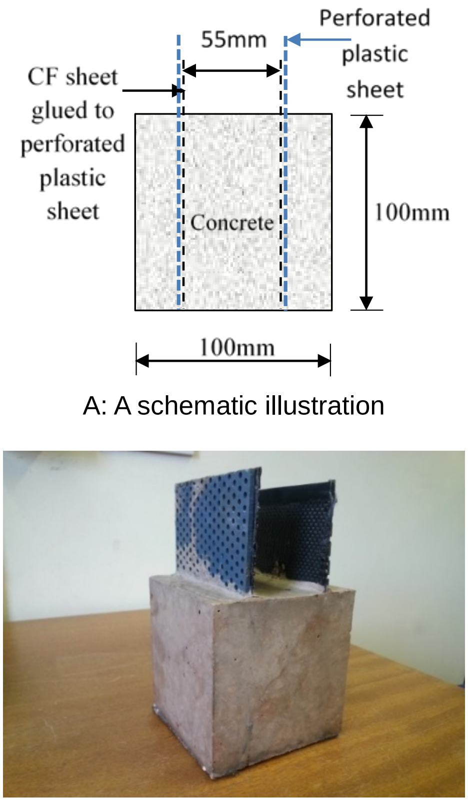
2.0 EXPERIMENTAL PROGRAMME

2.1 Mix Design and Concrete Mixing

Portland limestone cement, CEM II/A-LL conforming to the British standard BS EN 197-1: 2011, was used for the concrete mixes at 390 kg/m^3. Natural sand of the maximum size of 4.75mm and a relative density of 2.47 was used for the fine aggregate at 580 kg/m^3. The coarse aggregate was the limestone of 10mm maximum size and 2.49 specific gravity and used at 1125 kg/m^3. The mix of concrete followed the British Standard, BS 1881-125:2013.

Four different chloride contents were prepared by adding pure NaCl in the mixing water. The added NaCl are 0, 1.5, 3 and 4.5% of the cement mass. Three different water to cement ratios (0.4, 0.5 and 0.6) were used for each chloride content. All the concrete samples were cured by being submerged in water of the same chloride content as used for their mixes. Full saturated curing ensures the even distribution of chloride ions in the concrete, therefore, making the test results more reliable. For each mix, three specimens were prepared for each property measured, and the average values are presented in this paper.

For internal electrodes configuration, 100 mm concrete cubes with embedded electrodes made of carbon fibre (CF) sheets were cast as shown in Fig. 1. The electrodes were made by gluing a flexible woven CF sheet on the flat surface of perforated plastic mesh plates. Two of the CF electrodes were casted upright keeping a certain parallel distance to each other in each concrete sample.



A: A schematic illustration

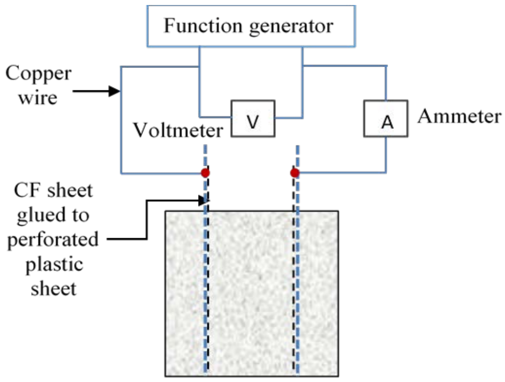
B: A photograph

Fig. 1. Concrete specimens with internal electrodes of CF sheets for resistivity measurement

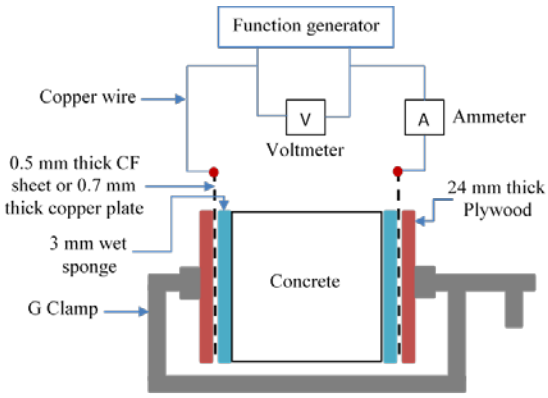
For the external electrodes configuration, additional 100 mm plain concrete cubes were made using the same concrete mixes in order to make a comparison between internal and external electrodes configuration.

2.2 Electrical Resistivity Test

Two-electrode method was used to perform the resistivity measurements. The schematic test arrangements of internal and external electrodes configuration are shown in Fig. 2.A and Fig. 2.B, respectively. In the case of external electrodes, CF sheets and copper plates were used. Wet sponges with 1 mol/L of sodium sulfate (highly conductive solution) were inserted in between the concrete and the external electrodes and connected using G-clamp to ensure proper electrical connection (Newlands *et al*., 2008) as shown in Fig. 2.B. A plywood piece of 100x100 mm^2 was inserted in each side in between the G-clamp and the electrode to ensure a uniform pressure. This setup was necessary to facilitate low resistivity to get more reliable results (Newlands *et al*., 2008).



A. Internal electrodes



B. External electrodes

Fig. 2. Schematic of experimental setup of electrical resistivity measurement for specimens with internal and external electrodes

In this study, at first, influences of electrode materials and configurations on the electrical resistivity measurement were evaluated under various applied AC frequencies in a range from 1 Hz to 10 kHz. In theory, the optimum frequency or electrode configuration should produce the lowest resistance (Katwan, 1988), this combination were later used in subsequent experimental studies.

The electrical resistivity of the concrete based on the obtained concrete resistance was calculated as in equations (1) and (2) (Hornbostel *et al*., 2013):

$$\rho = R\frac{A}{L} \tag{1}$$

$$R = \frac{V}{I} \tag{2}$$

where ρ is the electrical resistivity, R is the electrical resistance according to Ohm's law, V is the applied voltage (the voltage magnitude of 3 V was used for the saturated specimens and 6 V used for unsaturated specimens because of the increased resistivity), I is the measured current, A is the cross-sectional area of the electrode perpendicular to the current flow and L is the distance between the two electrodes.

Firstly, concrete specimens were tested at the saturated-surface-dry state. After that, the 100 mm cubes were cut into small cubes of 50 mm nominal dimension under wet condition using diamond cutting saws. The downsized samples, which will shorten the time required to achieve the equilibrium when the specimens have uniform moisture distribution under a certain environmental condition, were then transferred into a humidity-controlled chamber, which had a constant temperature of 21°C. Specimens were kept in the chamber until have reached a constant weight at constant relative humidifies of 35, 60 and 80%. The moisture content of specimens is evaluated by weighing them, and uniform moisture content is achieved when 24 h variations in mass is less than 0.01g (Villagrán Zaccardi and Di Maio, 2014). Electrical resistivity was thereafter measured for each RH. Finally, all specimens were transferred to a drying oven at (100±5)°C until reach a stable dry condition. Then, they were measured for the oven dried resistivity test.

3.0 RESULTS AND DISCUSSION

3.1 Effect of Frequency, and Electrode Material and Configuration

Low and high frequency ranges were investigated to locate their effects on the measured resistance of concrete specimens at saturated and surface dry (SSD) condition. Most of the time, The SSD condition is chosen as the standard moisture state (Chen *et al*. 2014). Internal and external electrodes were used, respectively. Frequencies in the range of 1 Hz to 10,000 Hz were considered to be able to provide sufficient data to identify the true resistivity of the studied specimens. A single frequency, however, should be used if comparison is required.

Figure 3 shows the variation of resistance values with the applied frequency when external electrodes made of copper were used to measure the electrical resistance. Concrete specimens produced using w/c ratio of 0.5 and mixed with and without sodium chloride (0% NaCl and 3% NaCl) were examined in this test. It can be seen that frequency has a significant influence on the resistance when external electrodes are used. The use of a high frequency of 10,000 Hz reduced the measured resistance of the two mixes by about 58% on average, compared to 1 Hz frequency. These results indicate that the measurement at low frequencies leads to significant increase in resistance values causing overestimated results and should be noted during electrical resistance tests. Farnam *et al*. (2015) highlighted that the characteristics in low frequency region are primarily influenced by conditions at the electrode-concrete interface.

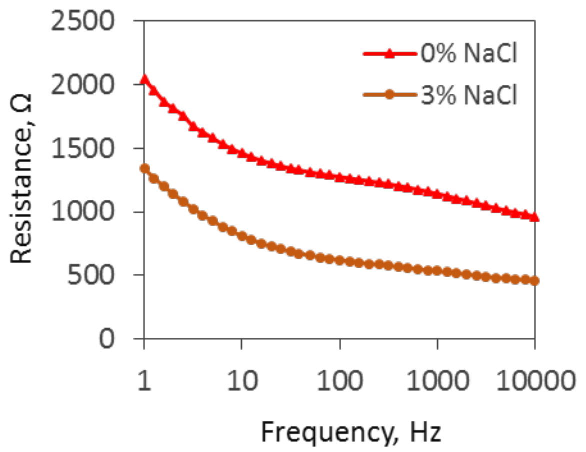


Fig. 3. Influence of applied frequency on electrical resistance measured using external electrodes of copper plates

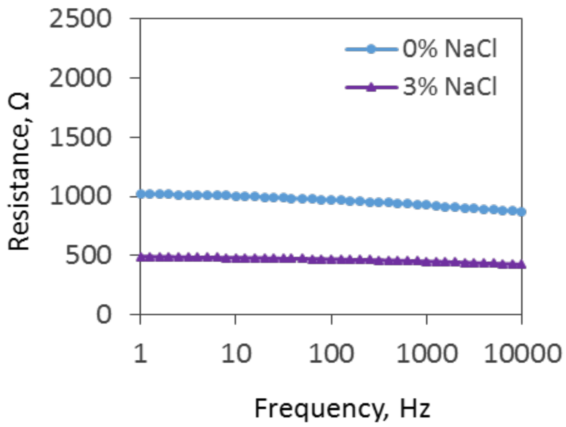


Fig. 4. Influence of applied frequency on electrical resistance measured using internal electrodes of CF

The influence of electrode-contact interface on the measured electrical resistance was eliminated or reduced to be minimum using internal electrodes made of CF as shown in Fig. 4, where the influence of the frequency on the measurement is very limited, and the electrical resistance was almost unchanged in the test frequency range for the two mixes. Therefore, a wide range of frequency can be used for the resistivity measurement when using internal electrodes.

Figures 5 and 6 compare the values of electrical resistance of the two mixture samples measured using the internal electrodes and two different external electrodes at different frequencies. It is very clear that the resistance values at low frequency using internal electrodes is much lesser than external electrodes of copper which is commonly used for measuring electrical resistivity of concrete. For instance, at low frequency of 1 Hz, using internal electrodes of CF reduced the measured resistance using external electrodes of copper from 2041Ω to 1020Ω (50% less) and from 1338Ω to 491Ω (63% less) for the concrete specimens incorporated with 0% and 3% NaCl, respectively.

On the other hand, values obtained using external electrode of CF at low frequencies is also less than that obtained using external electrodes of copper plates as the values of resistance dropped from 2041Ω to 1333Ω and from 1338Ω to 620Ω when the concrete specimens mixed with 0% and 3% NaCl, respectively. The result indicates that not only the contact interface can affect the resistivity measurement but also using external electrodes of CF gives lower resistance compared to using copper plates at low frequencies and that could due to flexibility of CF which can provide better contact to the concrete surface. However, the differences between the measured resistivity decrease as the applied frequency increases. All the measurements using different approaches tend to become very close at high frequencies of 10,000 Hz. However, using internal electrodes of CF sheets is a more reliable method and can improve the accuracy in different situations due to the following advantages. Firstly, it can be used to measure the resistivity of unsaturated specimens without affecting the internal water content that lead to underestimating values. Secondly, it eliminates any potential extra resistance due to the use of conductive medium even at fully saturated specimens. Finally, a wide range of frequency can be used with a little influence on the measured resistivity as discussed previously. All of these benefits are attributed to the stable contact zone between the internal electrodes and the concrete.

Katwan (1988) stated that the most acceptable frequency is the one that causes minimum electrode perturbation, lesser polarization effect and gives lower resistance value. Accordingly, in this study, a test frequency of 10,000 Hz and internal electrodes of CF were adopted as the most appropriate frequency and electrode configuration to investigate the most influencing factors on the resistivity of concrete for different mixes under various conditions.

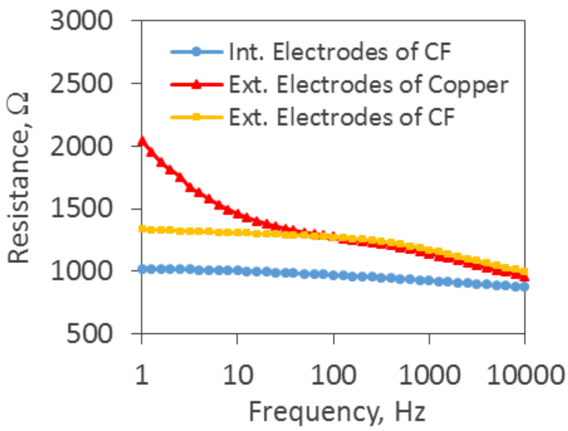


Fig. 5. Influence of applied frequency on electrical resistance of concrete specimens mixed with 0% NaCl measured using internal and external electrodes

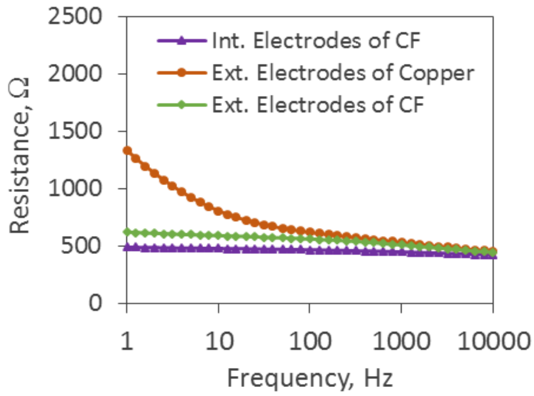


Fig. 6. Influence of applied frequency on electrical resistance of concrete specimens mixed with 3% NaCl measured using internal and external electrodes

3.2 Effect of Chloride

In order to obtain an accurate chloride contents for quantitative approach after wet curing, total chlorides analysis was conducted for all the concrete specimens with different amounts of added sodium chloride and water to cement ratios using potentiometric titration method described in ASTM C1152/C1152M-12. Three cylindrical cores of the size 12 mm × 100 mm (diameter × length) evenly distributed along the central line of a cubic sample (100 mm × 100 mm × 100 mm) were taken from each mix sample and crashed into powder. The powder of the three cylindrical cores were mixed together to represent the sample of each mixture. The obtained results is presented in Fig. 7. It can be seen that for a certain amount of NaCl, total chloride by weight of concrete increases slightly with the increase of w/c ratio. The result was reasonably related to the curing method, since when the concrete samples were submerged in the same salty water containing the same NaCl contents as that added during mixing, the high w/c ratio resulting in a high porosity would leave more chloride ingress into the concrete in the curing process.

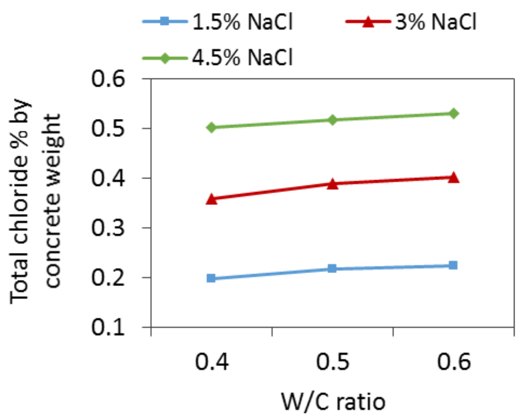


Fig. 7. Total chloride as a function of NaCl and w/c ratio

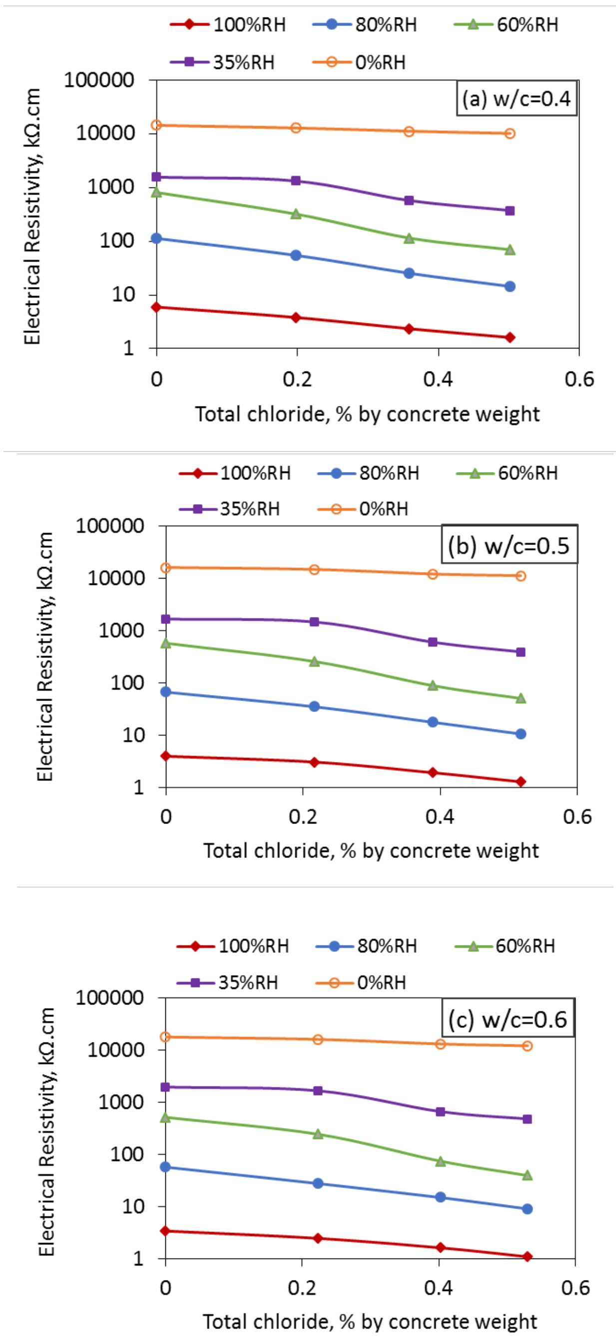


Fig. 8. Influence of total Cl on electrical resistivity measured using internal electrodes of CF sheets at varied RH and w/c

Figure 8 shows the relationship between the total chlorides and the resistivity of all the concrete specimens at different relative humidities (RH) and w/c ratios. As expected, at all the w/c ratios, the resistivity decreases as the chloride content increases. It can be also seen that the electrical resistivity shows a noticeable decrease at high amount of chloride, particularly with those having high levels of RH, and the specimens with no chloride has the highest electrical resistivity. For instance, At 0.4 w/c and 100% RH, the resistivity values of the concrete specimens which are incorporated with 0.2, 0.35 and 0.5% total Cl dropped approximately to 63, 42 and 27% respectively of those are free of chloride.

Similar tendency of reduction in the resistivity due to increasing of chloride has been observed under different values of w/c and RH. The fact that electrical resistivity becomes lower as the total Cl increases is attributed to that high amount of chloride in the pore solution decreases the resistivity of pore solution (Farnam *et al*., 2015). The influence of chloride on concrete resistivity was studied by Hunkeler (1996) and reported that adding of 0.45% chloride by concrete mass reduced the resistivity by only 27%. It should be noted that the risk of a specific amount of chlorides on concrete resistivity is dependent on the type of cement and additives used in concrete (Whiting and Nagi, 2003). Cements blended with pozzolanic materials have higher resistivity than ordinary Portland cement (Medeiros-Junior and Lima, 2016). From Fig. 8, it can also be concluded that for a fixed w/c, reducing the RH decreases the effect of chloride on resistivity. However, for a certain chloride content and w/c ratio, for example for the specimens with 0.4 w/c and 0.2% chloride, reduced the RH from 100 to 80, 60 and 35% increased the resistivity from 3.8 to 54.6, 319.4 and 1315 kΩ.cm, respectively which indicates that RH has a significant impact on the resistivity much more than the influence of chloride.

3.3 Effect of Water to Cement (w/c) Ratio

As stated in the previous section, total chloride is changing with water to cement ratio, but for comparison, a single chloride content is required to study the influence of water/cement ratio on the measured resistivity for the mixes of different chloride contents and relative humidities as shown in Fig. 9. It is worth noted that the values of this Fig. were derived from the figures in previous section using polynomial fitting with an R^2 of greater than 0.99. As can be noticed from Fig. 9, there is a general tendency towards lower resistivities with increasing water to cement ratio for all mixes of different Cl contents at high RH (100, 80 and 60%). For example, increasing w/c from 0.4 to 0.5 and from 0.4 to 0.6, about 35 and 43 % reduction on average was observed for the specimens with 0%Cl. This is due to that water to cement ratio is a major parameter in determining the pore structure of concrete and ions concentration of concrete pore solution. Increasing the water to cement ratio will increase the pore size and the connectivity of pore network, and decrease the electrical resistivity of concrete at high water content.

It is also evident that for a certain w/c ratio, decreasing RH increased the resistivity by tens to hundreds of kΩ.cm. For instance, at w/c of 0.4 and 0%Cl specimens, decreasing RH from 100 to 80% and from 100 to 60%, the electrical resistivity increased from 6 to 113 and from 6 to 805 kΩ.cm respectively. The same trend has been obtained for the specimens with the other w/c ratios and amount of chlorides indicating that moisture content is the main controlling factors and seems to be much important than the influence of w/c.

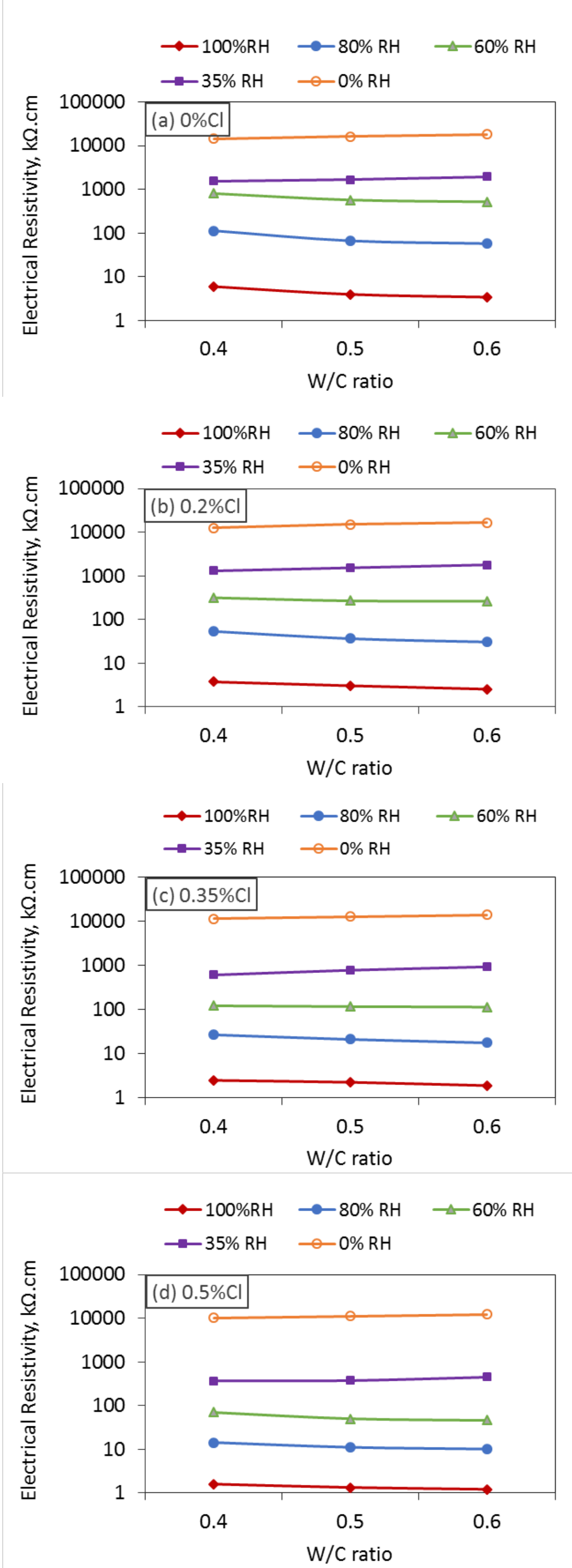


Fig. 9. Effect of w/c ratio on electrical resistivity of concrete specimens at various relative humidities and chloride content

The trend of reduction in resistivity when w/c increased is in agreement with previous observation reported by Monfore (1968), Gjørv *et al*. (1977), Lübeck *et al*. (2012), Chen *et al*. (2014) and Van Noort *et al*. (2016), but different values of reduction were found due to variation in the experimental setup and the technique used for the resistivity measurement and some studies were just limited to free chloride and wet exposure conditions. Another study have noted no significant influence on the electrical resistivity of unsaturated specimens at 65% RH when w/s ratio changed from 0.4 to 0.6 (Medeiros-Junior and Lima, 2016).

However, at low RH, 35% RH and oven-dried (0% RH) as illustrated in Fig. 9, resistivity increases with increasing water/cement ratio which is the opposite of the relationship presented for high levels of RH, which means the resistivity of concrete is affected directly by the degree of saturation not w/c. Interestingly, the resistivity of specimens with w/c of 0.6 is approximately 29% on average higher than that of the specimens with w/c of 0.4. This is due to that at low water contents, most pores, particularly of big sizes, are empty and occupied by air, and air is electrically non-conductive. A 40% of RH has been identified by Hunkeler (1996) for capillary water to be available and any water below this level is considered not conductive and the resistivity tends to be very high. However, A study by Gjørv *et al*. (1977) showed that resistivity decreases with w/c correspondingly even at low RH of 40% and it is more pronounced compared to wet exposure and high RH conditions. Another study by Chen *et al*. (2014) on concrete specimens with low RH at oven dry or 40% RH using four-point Wenner method and observed such measurements are inappropriate as they were too dry to form conductive paths. Such results suggest that a correlation between electrical resistivity of concrete with amount of water is very important for a clear vision and to provide quantitative approach for practical application.

4.0 CONCLUSION

Based on the experimental results, the following conclusions can be drawn:

1. To obtain a reliable measurement, low frequencies should be avoided as it overestimates the measured resistivity particularly in the case of using external electrodes. High frequency of 10,000 Hz is recommended.

2. Using internal electrodes of CF sheets is a more reliable, which improve the accuracy of the resistivity measurement of both saturated and unsaturated concrete specimens.

3. External electrodes of CF sheets could be an alternative choice for copper plates to measure the resistivity of concrete, particularly when inert and flexible material for better contact interface are required.

4. The inversely proportional between w/c ratio and resistivity is only valid when degree of saturation is high. At low values of RH (≤ 35%), about 29% an increase in the resistivity was observed when w/c increased from 0.4 to 0.6.

5. Amount of chloride and w/c have an important influence on the resistivity of concrete. For the specimens with 0% Cl at saturated condition, increasing w/c ratio from 0.4 to 0.5 and 0.4 to 0.6 led to 35 and 43% reduction in the resistivity value, respectively. While increasing total chloride content from 0 to 0.5% (by weight of dry concrete) for the specimens with w/c ratio of 0.4 at saturated condition, the resistivity decreased by 73%. However, RH has a significant effect on the resistivity much more than chloride content and w/c ratio. For the specimens of 0% Cl and 0.4 w/c, decreasing RH from 100 to 80% and from 100 to 60%, the resistivity increased from 6 to 113 and from 6 to 805 kΩ.cm, respectively.

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