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Publication

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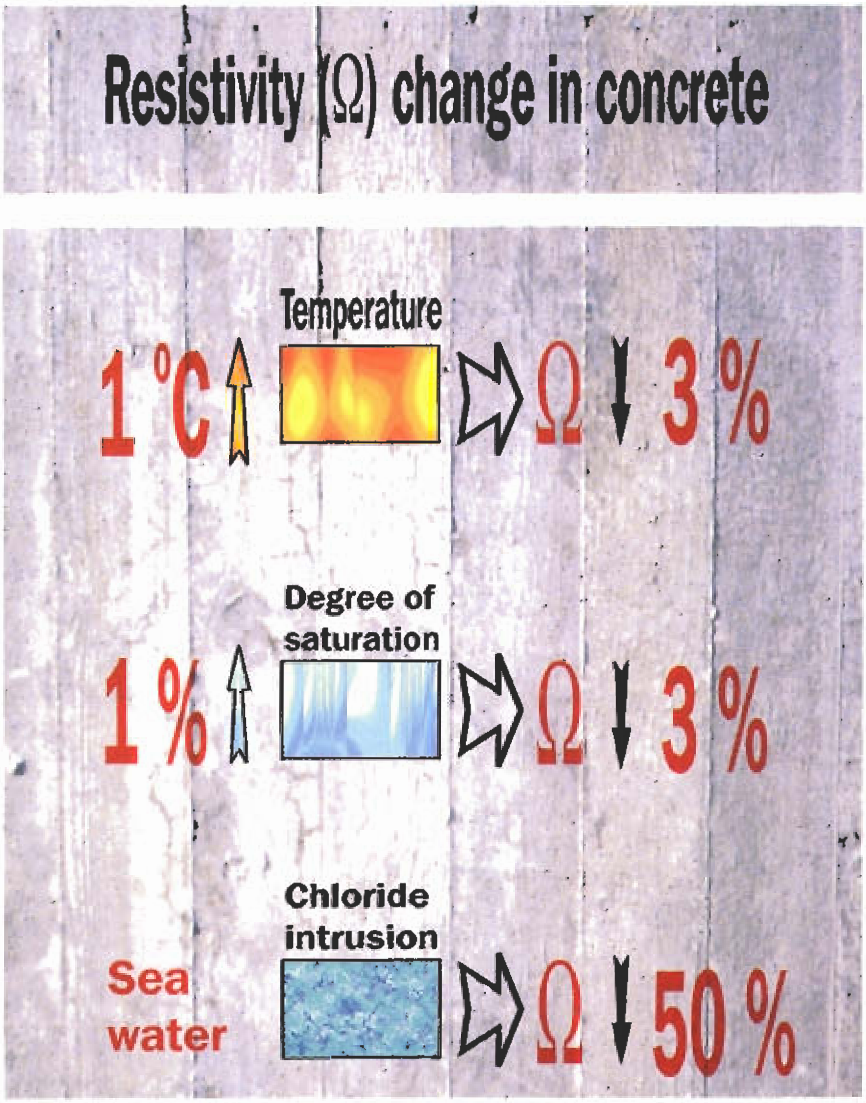

**Norwegian Public Roads Administration**
Directorate of Public Roads

Norwegian Road Research Laboratory

Publication no. 80

*William Elkey and Erik J. Sellevold*

# Electrical resistivity of concrete

Directorate of Public Roads
Norwegian Road Research Laboratory
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# Preface

In 1993, the Norwegian Public Roads Administration together with the Nordland County Road Administration started a rehabilitation project on the Gimsøystraumen Bridge in Nordland County, Norway.

This project had a dual purpose. One was to build up national competence in Norway on coastal concrete bridge status by focusing on one particular bridge, Gimsøystraumen. Methods to determine the degree of passivity and corrosion state of the reinforcement were to be systematically tried out, as well as different types of sensor systems installed to provide continuous data on state changes over time. The other purpose was to test out different preventive measures and to undertake a complete rehabilitation of the bridge.

The present report is part of the status assessment work. It concerns the use of concrete resistance data as a means to monitor moisture content changes in the concrete cover over the reinforcement over time. The project included literature studies and laboratory experiments on the materials and environmental factors influencing the electrical resistance of concrete, and was carried out at the Norwegian Road Research Laboratory, Oslo.

The work was carried out by William Elkey MSc under the supervision of Prof. Erik J. Sellevold, Dr. Elisabeth Schjølberg and Dr. Håvard Østlid. Mr. Elkey was associated with the Road Research Laboratory (Feb. - Nov. 1994) on an internship sponsored by the Valle Foundation, University of Washington, Wa., USA. Facilities and practical support for the project was provided by the Road Research Laboratory, Oslo, and the Gimsøystraumen Project.

*Norwegian Road Research Laboratory, June 1995*

# Content

# Summary

The purpose of the present work was to explore the use of electrical resistance measurements in field concrete as a means of monitoring changes in the moisture content of the concrete over time. Presently the only practical means of monitoring the moisture state of field concrete is to measure relative humidity (RH) over time. The RH defines the thermodynamic state of the pore water, but not the amount, which probably is more important than RH for several durability properties. Hence our interest in resistance measurements.

The work is presented in two parts: A literature review and the results of an experimental program carried out in the laboratory.

The literature review covers existing knowledge of the effects of experimental factors such as method of contact between electrode and concrete, applied voltage and frequency. The importance of concrete mix proportions and choice of mix components (cement, silica fume, curing temperature etc.) are covered, as is the more scarce information on the important environmentally determined parametres - the moisture content, the pore water composition in the concrete and the concrete temperature.

The experimental program focuses on the three factors believed to be most important in interpreting continuous resistance measurements in field concrete: Moisture content (expressed as DS = degree of saturation), chloride concentration in the pore water and concrete temperature.

The results demonstrated the extreme importance of the contact between the electrode and the concrete - particularly when measurements are carried out at less than saturated moisture contents.

Over the whole degree of saturation range tested the DS-value has the greatest effect on the electrical resistance, which increases several orders of magnitude from wet to dry state. However, for Norwegian coastal bridges the practical DS range is about 70 to 100 %, and in this range the resistance of concrete changes roughly as follows:

- 3 % per °C temperature change
- 3 % per % change in degree of saturation
- 50 % due replacement of pore water by 3 % or 6 % NaCl solution.

Clearly more experimental work must be carried out to better resolve the influence of chlorides. From the results as a whole it is quite clear that even a rough monitoring of changes in moisture content in field concrete by means of resistance measurements requires accurate simultaneous temperature measurements. Any change in the chemical composition of the pore water is likely to effect the resistance values significantly.

# 1 Introduction

The moisture condition and its variation in a concrete structure are probably the most important factors for the durability of the structure, regardless of the deteriorating mechanism. The rates and consequences of reinforcement corrosion, freeze/thaw attack, alkali-aggregate reactions, etc. all depend strongly on the moisture condition of the concrete. Consequently, it is of obvious importance to obtain reliable information on the moisture state in concrete structures. Such information is, however, scarce in literature. One reason is the practical difficulties in obtaining reliable information. The most obvious method is to remove concrete from the structure in a non-disrupting manner, seal the pieces and then make measurements in the laboratory. This is certainly the most accurate method, but is laborious and somewhat destructive; hence very few systematic investigations have been reported.

The most practical method would be to install a monitoring system allowing periodic readings to be taken automatically. Recently several types of relative humidity (RH) probes have become available on the market, opening the possibility of continuous recording of RH-values at selected positions. In our opinion it has not yet been shown that such probes are reliable over time in natural exposure conditions. For laboratory work the probes can give reliable results only when the temperature is controlled and frequent calibrations are performed. However, RH-data alone only defines the thermodynamic state of the pore water, and not directly the amount of the pore water (or degree of saturation). For many deterioration mechanisms, notably freeze/thaw attack and probably the rate of corrosion, the degree of saturation is the relevant parameter. The relationship between RH and the amount of pore water (sorption isotherm) for concrete show a large hysteresis; i.e., the difference between the water contents at a given RH can be quite large and depends on whether a given RH-value is achieved by adsorption or desorption. In addition, the RH-value exerted by the pore water is influenced by the concentration and types of dissolved ions. Consequently, even reliable RH-records would give incomplete information about the moisture state in a concrete structure.

Electrical resistivity measurement is an alternative, potentially useful method to monitor the moisture state of in-situ concrete, aside from the intrinsic value of such data for the corrosion process [1]. Electrical resistivity in concrete is expected primarily to be a function of the degree of water saturation of a given concrete (rather than the RH). However, resistivity also depends on temperature and pore water composition. The present work includes a review of existing literature on resistance measurements in concrete as well as the results of well-controlled laboratory experiments. The primary purpose was to evaluate the use of resistance measurements as a means of monitoring the moisture state in concrete.

The study presented is in two parts: first, a review of previous studies and second, a laboratory investigation. The review will examine the trends observed among many studies, to identify similarities as well as discrepancies. In addition, it will focus on the methods used in their determination of the electrical resistance or resistivity of concrete, in an attempt to understand how results can be influenced by, for example, electrode type, method of contact, the voltage and (in the case of alternating current) frequency of the measuring instrument, and the specimen dimensions. The laboratory investigation focuses on three important parameters that affect the electrical resistivity of a given concrete: moisture condition, temperature, and chloride concentration in the pore water.

# 2 Literature review

## Durability and Electrical Resistance

Pore water is an electrolytic solution containing, mostly $K^+$, $Na^+$, $Ca^{++}$, $SO^-$ and $OH^-$ [2]. Additional ions (such as chlorides) can also be present due to infiltration from other sources (such as seawater), increasing the concentration of ions in the pore water and, presumably, reducing the electrolytic resistance. The other major factors for concrete resistivity are the pore structure and degree of saturation. The resistivity is the combined result of many factors, and is therefore sometimes used as an indicator of the ability of a given concrete to protect the steel from corrosion. The first studies of electrical resistivity in concrete came about when the industry needed to develop a highly resistive concrete for railroad ties, as electrical signals were being sent through the rails [3, 4], but recently corrosion detection and prevention have been the main focuses of these studies. It has been shown that the resistivity of the concrete is a controlling factor in the rate of corrosion [5, 6].

The level of resistivity needed to prevent corrosion has been examined in various studies, with varying results. Most studies confirm that a resistance of 5,000 Ohm-cm or lower will very likely result in corrosion occurring [7], but the level of resistivity necessary to protect from corrosion is less defined. Several studies have stated that resistance greater than 10,000 Ohm-cm, although one study suggested 60,000 Ohm-cm is necessary for adequate protection [8]. Burke [9] discovered two specimens for which severe corrosion occurred at resistivities of 48,000 and 73,000 Ohm-cm, which clouds the range even further. Figure 1 shows the relationship between corrosion current ($I_{coir}$) and electrical resistance [1].

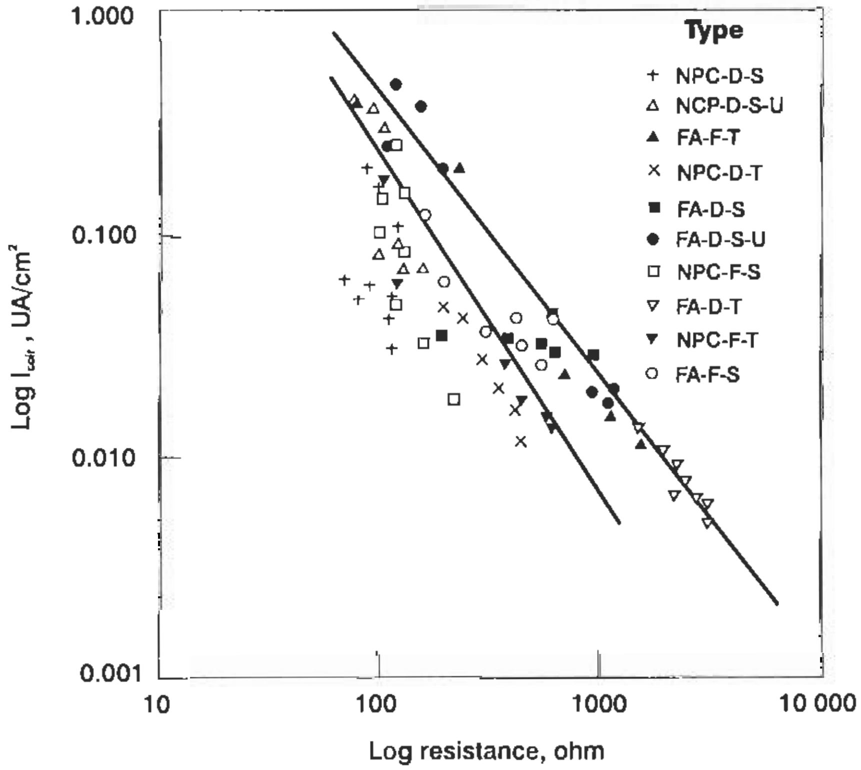

*Figure 1. Influence of Electrical Resistance on Corrosion Current, after Cabrera et al. [1].*

It is shown in this figure, although it is obscured by the many different mix types used, that a linear relationship exists between the electrical resistivity of the concrete and the corrosion current, indicating that the rate of corrosion in high resistivity concrete should be lower than that of lower resistivity, given the same exposure.

## Factors Influencing Electrical Resistance in Concrete

In saturated concrete electrical current is passed predominantly by the movement of ions in the pore water [10]. From this it can be inferred that, for saturated concrete, two fundamental factors deciding concrete resistivity are the pore structure characteristics (total porosity, pore size distribution and degree of continuity) and the total ionic concentration of the pore water. How these parameters can be altered and, in turn, alter the electrical properties of concrete has been compiled from various studies.

### Effect of Paste Volume

The influence of paste volume on concrete resistivity is shown in figure 2 [11]. It shows that, for a constant water/cement ratio, increasing the paste volume decreases the resistivity at a rate of approximately 1% per 1% paste. Changing the water cement ratio, while altering the particular resistivity level for each concrete, does not alter either the direction or magnitude of this trend. The increase of paste content creates more channels for electrolytic liquid (pore water). Therefore this trend is consistent with a simple composite model for concrete, with the paste as the "conducting" component.

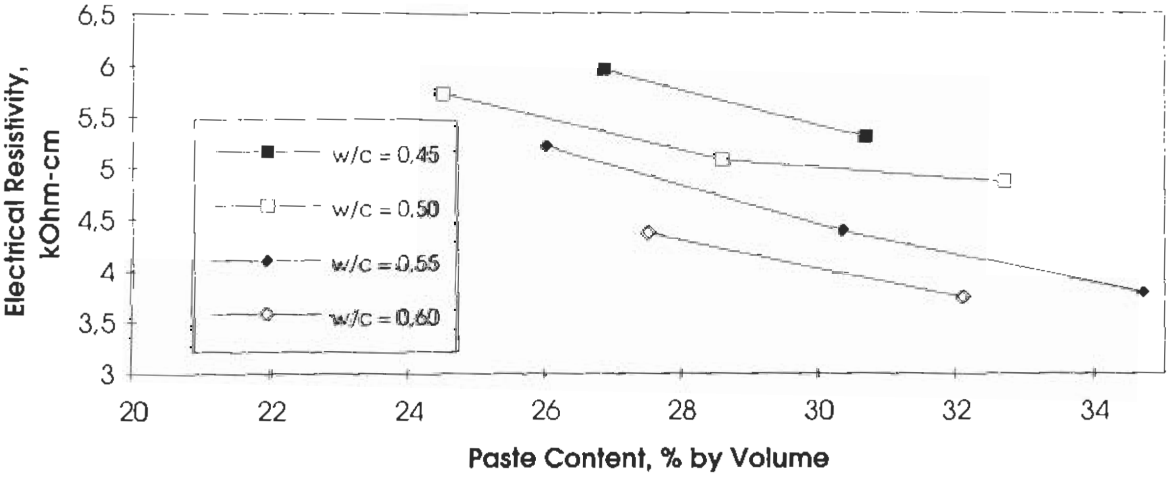

*Figure 2. Influence of Paste Content on Electrical Resistivity of Saturated PCC, after Hughes et al. [11].*

### Effect of Cement Type

Intrinsically, the type of cement used in a particular mix has an impact both on the pore structure characteristics and the pore water chemistry. Figure 3 [12] shows the relationship between cement type and resistivity for concrete made with four portland cement types: two ordinary portland cements (OPC1, OPC2), a modified portland cement containing 20% fly ash (MP) and a high strength portland cement (HS).

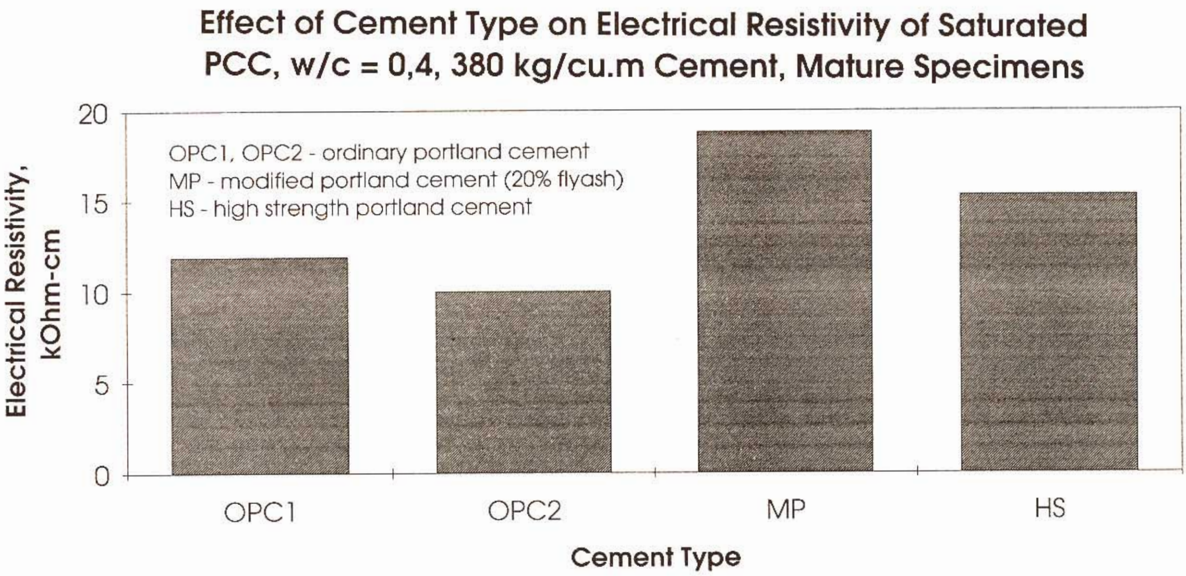

*Figure 3. Influence of Cement Type on Electrical Resistivity of Saturated PCC, after Vennesland et al. [12]*

This figure shows that even for two types of ordinary portland cement there is a noticeable difference in resistivity between the concretes made with ordinary portland cement from different manufacturers. MP and HS concretes, however, both showed a substantial increase in electrical resistivity when compared to OPC. Other studies have shown much larger differences in resistance. For example, Hammond [3] showed that a high alumina cement had a mature resistivity of 10 times that of OPC with the same water/cement ratio and curing.

## Effect of Water/Cement Ratio

The water/cement ratio in concrete is a major factor in determining the pore structure of hardened concrete. It is known from other studies that as the water/cement ratio increases, the pore structure becomes coarser and more continuous. From this it can be inferred that an increase in the w/c-ratio will cause a decrease in the electrical resistivity. Figure 4, which compiles the data from three independent studies [9, 11, 13], shows a linear trend with a rate of change of approximately -0.22 kOhm-cm/0.01 w/c ratio.

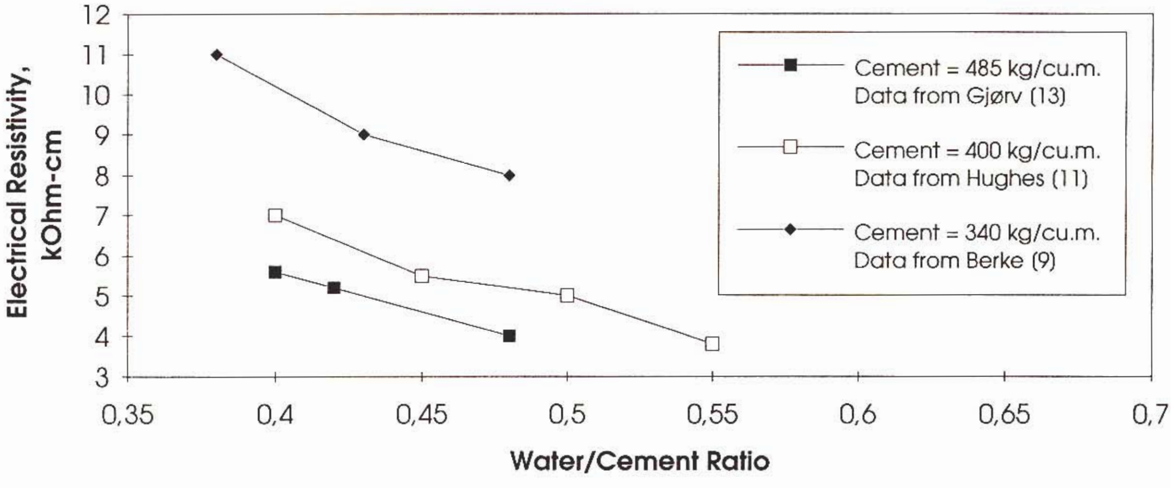

*Figure 4. Influence of Water/Cement Ratio on Electrical Resistivity of Saturated PCC [9, 11, 13].*

Figure 4 shows that the dependance of this trend on other concrete parameters (i.e., curing, cement type, silica fume content) is most likely not substantial given the limited information on the particular mix designs and curing procedures for these studies. In addition, the increase in paste content, while decreasing the resistivity, does not alter these trends.

## Effect of Curing Temperature

In 1993, Hauck [14] performed chloride migration studies to examine the effect of curing temperature and silica fume content. During this process a record of the electrical resistivity, both before and after chloride migration (steady state chloride transport in a 12 V field), was kept. Figure 5 shows how curing temperature effects the electrical resistivity of PCC (measured before the migration test) for varying silica fume contents.

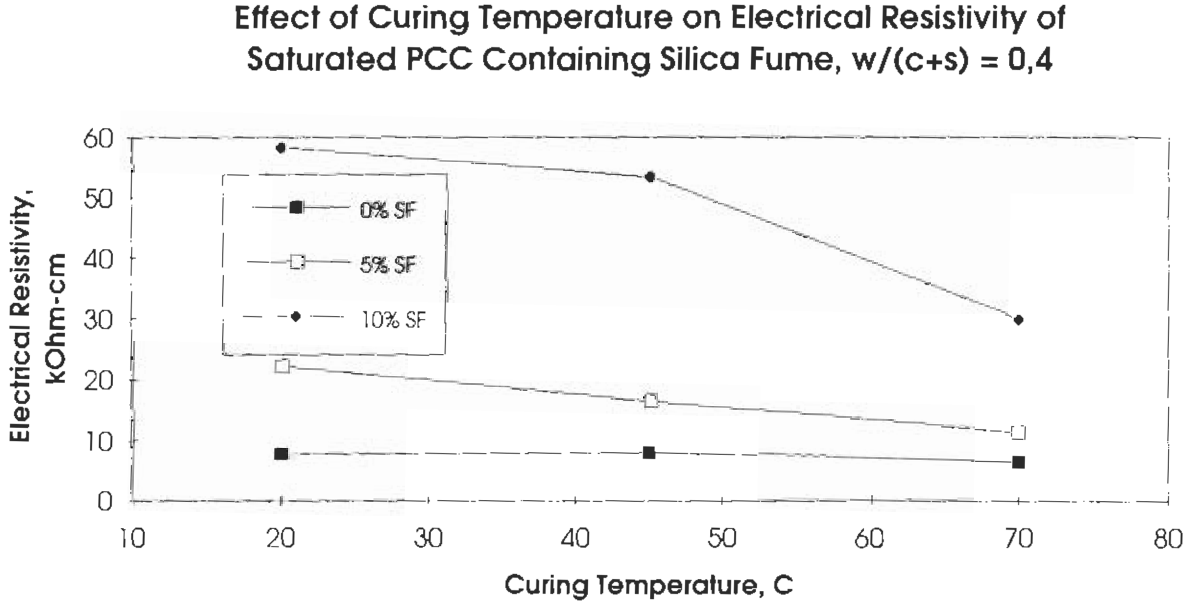

*Figure 5. Influence of Curing Temperature on Electrical Resistivity of Saturated PCC, after Hauck [14].*

Figure 5 shows that as the curing temperature increases the electrical resistivity decreases, and that this trend becomes much more noticeable as silica fume is added. This may indicate that the concrete has a different ionic concentration in the pore water, but more likely shows that the pore structure itself becomes coarser and more continuous due to the increased curing temperature, as has already been shown by low temperature calorimetry.

## Effect of Silica Fume

It is well understood that when silica fume (or fly ash) is added to a concrete mix it results in a much finer pore structure [9] as well as lower ionic concentration in the pore water [15]. Both factors are expected to increase the resistivity. Figure 6 illustrates the relationship between silica fume content and electrical resistivity, as collected from two independent investigations [9, 14].

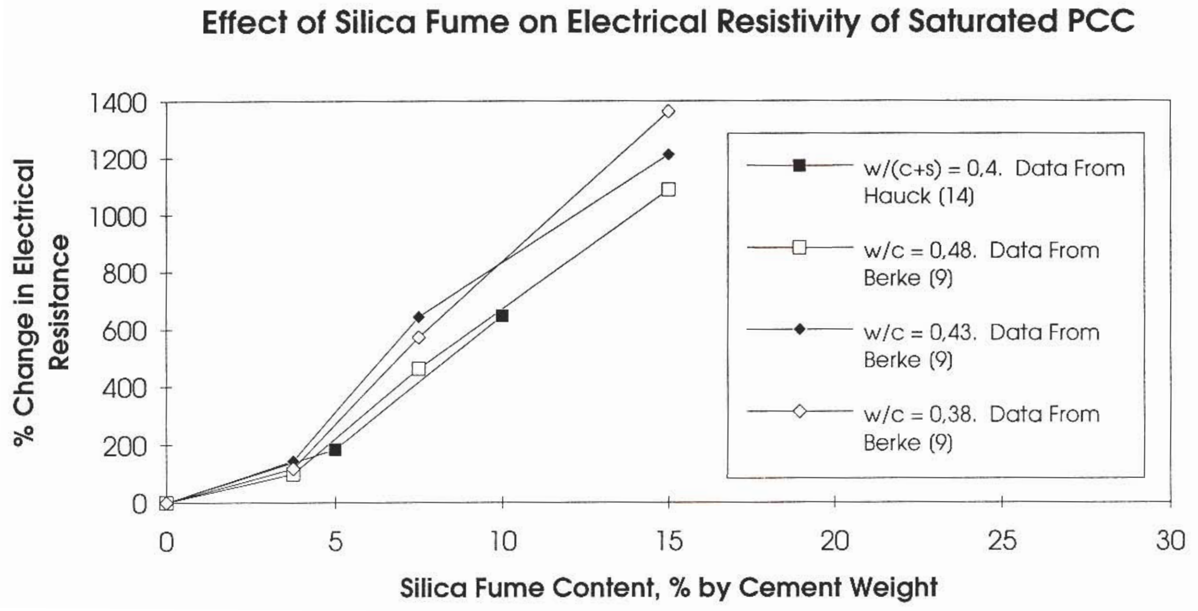

*Figure 6. Influence of Silica Fume on Electrical Resistivity of Saturated PCC [9, 14].*

Figure 6 shows that the electrical resistivity, as expected, increases substantially with increasing silica fume content. The differences in resistivity among mixes of various w/c-ratios, in addition, appear to become more defined at higher concentrations of silica fume. In an extreme case, Hansson [10] showed that dense mortar containing silica fume (w/c = 0.15) had a mature resistivity of 200 kOhm-cm.

## Effect of Temperature

Like all materials, concrete's electrical properties are affected by temperature. This phenomenon is also complicated by the change in the pore water chemistry that occurs along with change in temperature. At higher temperatures, more ions will dissolve into the pore water, and then precipitate out as the water cools. Woefl and Lauer [2] performed independent studies on the effect of temperature as well, superimposing their results with those of Monfore [9] and Spencer [16]. All three sets of data indicated a sensitivity of about 3% per degree C (with reference to 21 °C), with resistance increasing with decreasing temperature. Figure 7 shows a composite plot of data collected by Woefl and Lauer and data from Monfore superimposed on a curve developed by Spencer, showing the multiplying factor needed to change a resistance taken at other temperatures to that measured at 21 °C. The conformity of these independent studies suggests that this temperature phenomenon is independent of other concrete aspects, such as porosity, cement content, etc. It would be useful to compare the temperature effects on concrete resistivity to the temperature effects on a solution with the same ionic composition as pore water in the concrete.

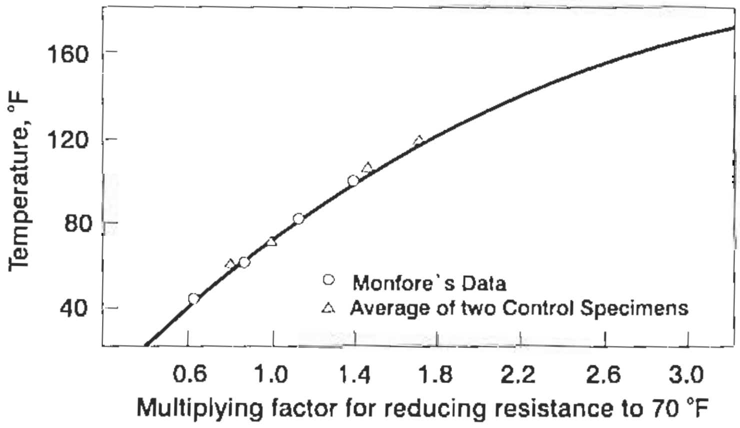

*Figure 7. Temperature Reduction Curve, after Woefl and Lauer ]2].*

The fundamental variation of phenomena such as resistivity to temperature can be expressed by the Hinrichson-Rasch Law:

$$R_2 = R_1 \cdot e^{A(1/T2-1/T1)} \qquad \text{(Equation 1)}$$

where

$R_1$ is the resistivity at temperature T1
$R_2$ is the resistivity at temperature T2
T1, T2 are temperatures (Kelvin)
A is the activation energy (Kelvin).

Figure 8 shows a typical plot of electrical resistivity versus the inverse of the absolute temperature based on data from Monfore and Hope [4, 8] for both concrete and paste specimens of different w/c ratios.

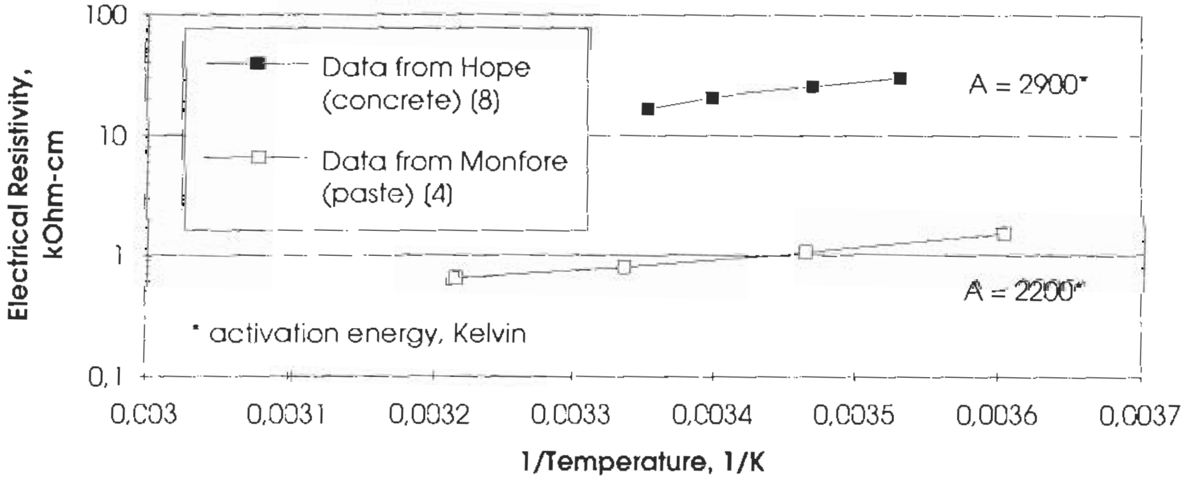

*Figure 8. Influence of Temperature on Electrical Resistivity of Saturated PCC [4, 8].*

Figure 8 shows that the relationship between resistivity and temperature is consistent with equation 1. Activation energies for the concrete and the paste were 2900 and 2200, respectively. Other sources have calculated values for A from 2000 to 5000, which represents approximately 3 % to 5 % per degree C at 21 °C. The most commonly observed is around 3000 [8]. Other studies have shown that this sensitivity can vary depending on the moisture condition [17], but further studies should be performed to examine this effect.

## Effect of Chlorides

As chloride intrusion is a chief cause of corrosion of the reinforcing steel, the influence of chlorides on the electrical resistivity of concrete has been of interest in previous studies, particularly involving the addition of chlorides to the mixing water. It is expected that the additional ions introduced into the pore water will cause a decrease in electrical resistance, but as it is not understood how these ions will interact with those already present in the pore water, the amount of change in electrical properties is unknown.

Figure 9 shows the relationship between percent of calcium chloride (CaCl) added to the mixing water and the percent change in electrical resistivity of a mature (more than 3 months cured) concrete. This figure includes data from two studies [4, 13] and shows that the electrical resistivity drops quickly at low concentrations, but the marginal change after 2% CaCl addition is not as extreme, appearing to stabilize at approximately 50-60% of its original resistance. This suggests that after a certain level of chlorides is attained in the pore water additional chlorides do not substantially increase the total ionic concentration. However, it is also known that the concrete pore structure is altered when CaCl is added to a mix. Furthermore, such studies should also distinguish between chlorides in the concrete and those intruded after hardening.

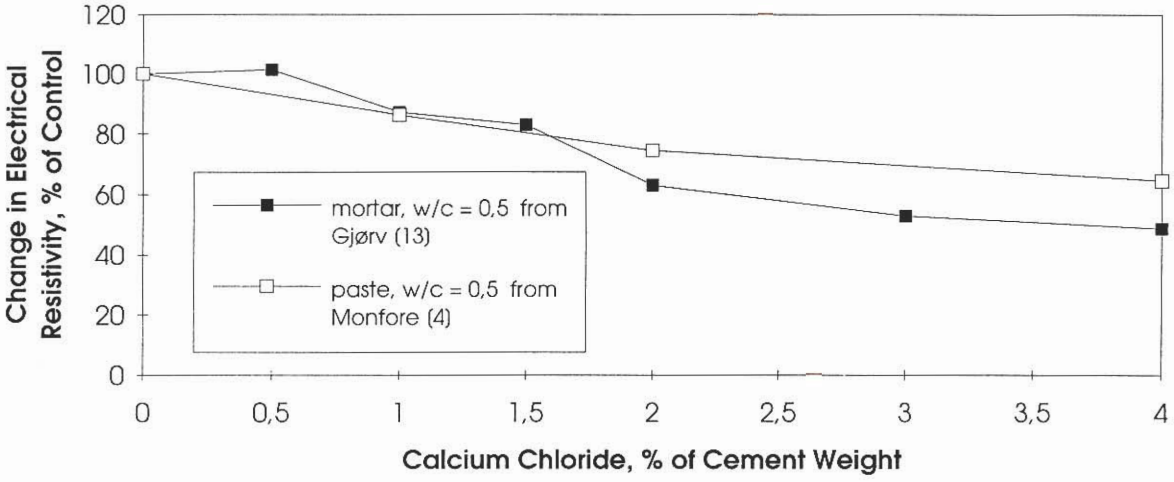

*Figure 9. Influence of Chlorides in Mixing Water on Electrical Resistivity of Saturated PCC [4, 13].*

The study by Hauck [14] showed a substantial decrease in resistance after the 12 Volt migration test was completed, as compared to before (particularly for concrete with silica fume). This is presumable a result of altered pore water composition since chloride ions are supplied to the pore water. Such experiments thus offer the opportunity to separate the chemical from the physical (pore structure) effect on concrete resistance.

## Effect of Moisture Content

Moisture content is a major factor deciding the electrical resistivity of concrete. As the pore water acts as an electrolyte with lower resistivity than that of the solid matrix, the moisture content is inherently a major factor affecting the concrete's electrical properties. As has been shown, a normal (OPC) saturated concrete has a resistivity between 1000-10,000 Ohm-cm, depending on mix parameters, while dry concrete reaches $10^8$-$10^9$, showing the importance of pore water on resistance [7]. Figures 10 [2] and 11 [13] show the effect of degree of saturation on electrical resistance.

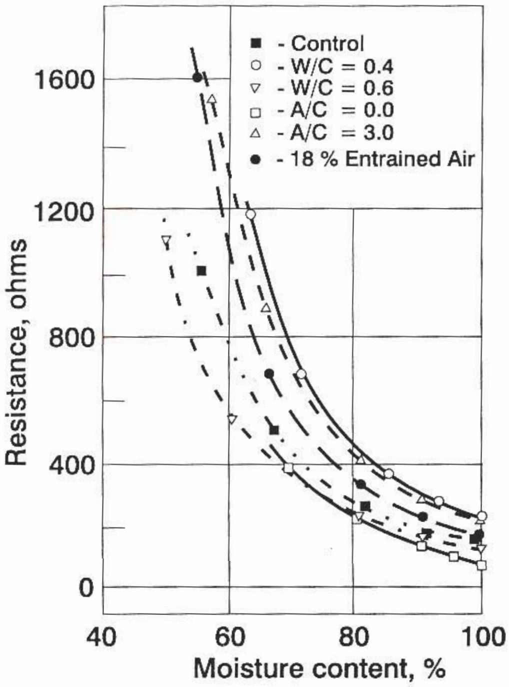

*Figure 10. Influence of Moisture Content on Electrical Resistance of PCC, after Woefl and Lauer [2].*

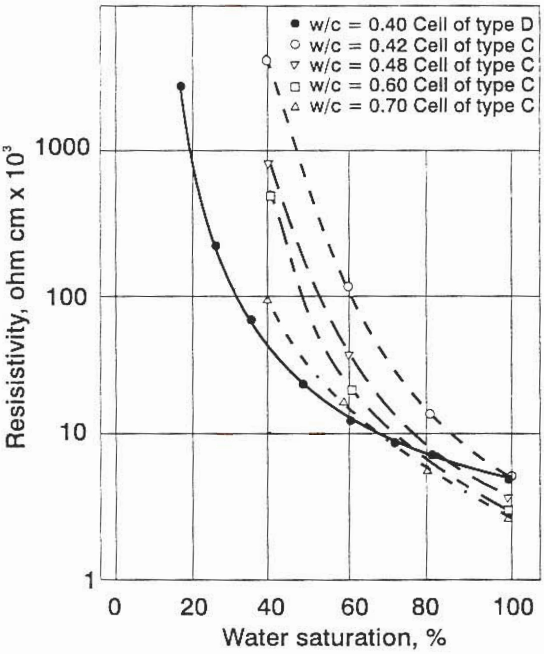

*Figure 11. Influence of Moisture Content on Electrical Resistivity of PCC, after Gjørv et al. [13].*

Both figures also show that decreasing w/c ratio increases the rate of change of resistance. It is also shown that the critical range, where the increase in resistance becomes more rapid, occurs at a high moisture content, 60 % to 80 % degree of saturation. This suggests the range where the pore water begins to lose continuity, decreasing the number of available electrical channels substantially.

## Review of Testing Methods

Of the testing procedures for electrical resistance reviewed for this study, the aspects that varied most frequently and which may have significant contributions to the results were: voltage type and/or frequency, specimen size and shape, electrode type, and the method of attaining proper contact. A summary of these parameters is shown in table 1.

**Table 1. Summary of test methods.**

| Study | Voltage type (frequency) | Specimen description | Electrode type | Method of contact |
|---|---|---|---|---|
| Monfore, 1968 [4] | DC (4-10 V)<br>AC (2-8 V)<br>(0.1-10 kHz) | cubes<br>(1" and 4") | brass plates (external) | stiff graphite gel |
| Hammond & Robsen, 1955 [3] | DC (55-3 kV)<br>AC (0.002-25 kHz) | cubes (4")<br>prisms<br>(4 x 4 x 1") | brass plates (external) | stiff graphite gel |
| Hughes, 1985 [11] | DC (4-8 V)<br>AC (10 V)<br>(1kHz) | cubes<br>(150 mm) | brass plates (external) | fluid cement paste (w/c = 0.5) |
| Woefl, 1979 [2] | AC (6 V)<br>(60 Hz) | prisms<br>(1 x 2 x 6") | slim rods (mat. N/A) | cast in |
| Hauck, 1993 [14] | AC | cylinders<br>(100 mm dia. x 51 mm) | iron mesh (external) | electrolytic solution |
| Hope, 1985 [8] | AC (1kHz) | prisms<br>(25 x 25 x 100 mm) | brass or steel rods | cast in |
| Bracs, 1970 [18] | not available | cubes (6") | steel wire | cast in |
| Cabrera, 1994 [1] | AC (10 V)<br>(1 kHz) | cubes<br>(100 mm) | brass plates (external) | fluid cement paste |
| Schiessl, 1993 [19] | AC (120 Hz) | not available | multi-ring electrode | cast in |
| Hansson, 1983 [10] | DC (3-9 V) | prisms<br>(90 x 70 x 50 mm) | perforated steel plates<br>(30 x 30 mm) | cast in |
| Bhargava, 1978 [20] | AC<br>(0.5-1.5 V)<br>(0.1-50 kHz) | prisms<br>(40 x 40 x 160 mm) | hardened cement paste w/ Pt black | cast in |

## Voltage and Frequency

Measurements of the electrical resistivity of concrete have been performed using both direct and alternating current at various frequencies. As concrete pore water is an electrolyte, the application of direct current causes a polarization potential, or back electromotive force (EMF), which alters the resistance readings [4]. A direct current also causes a net transport of ions in the electrolyte, thereby altering the electrolytic composition. The true resistance can then be calculated by using Ohm's Law.

$$R = \frac{Ea - Ep}{I} \qquad \text{(Equation 2)}$$

where

R is the electrolytic resistance (Ohms)
Ea is the applied potential (Volts)
Ep is the polarization potential/back EMF (Volts)
I is the electrical current (Amperes).

This method, while accurate, has been criticized as the resistance cannot be measured directly, but instead must be calculated using other electrical data. As shown in table 1, alternating current (AC) has been the more frequently used type for the measurement of electrolytic resistance due to the elimination of the polarization effect [3]. The range of frequencies used has been from 2 Hz in an early experiment by Hammond and Robson up to 50,000 Hz used by Bhargava. Voltage levels have ranged from 0.5 to 3000 Volts.

Recently impedance has been suggested as a more reliable measurement than resistance based on the voltmeter-ammeter (V-A) method, but some studies show that the difference is nominal for frequencies below 25,000 Hz [20]. Impedance is inversely related to both capacitance and resistance. As the frequency decreases, however, the capacitance of the concrete becomes much greater. Therefore, resistance has a greater influence on the impedance, and, as a result, impedance values are usually nearly identical to the resistance values measured.

It has been suggested that frequencies that are not multiples of 100 Hz are best for these measurements, as most interference from other sources would occur on these century points. A frequency of 108 Hz, consequently, has been suggested for the Multi-Ring

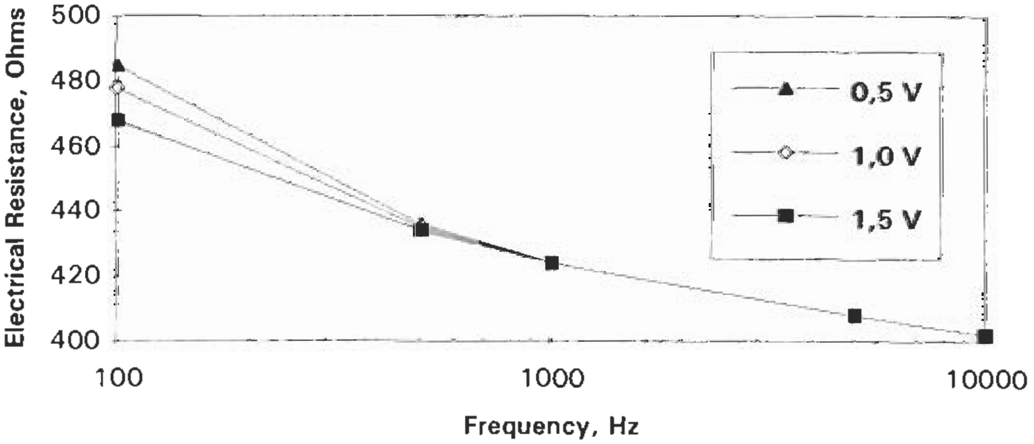

*Figure 12. Influence of Frequency and Voltage on Electrical Resistance of PCC, Bhargava [20].*

Electrode [19]. In 1978 Bhargava examined the resistance of concrete at different voltages and frequencies, the results of which are shown in figure 12 [20].

It is noticed in figure 12 that, after 1000 Hz frequency, the difference between the resistance measured at various voltages disappears and as a result he recommends, for the V-A method, a frequency of at least 1kHz should be used. Other studies, however, have not seen the same drop in the measured resistance with increased frequency. Calleja [21] showed in his study that the decrease in resistance from 40 to 20,000 Hz was only 10%, about half the magnitude of change shown in figure 12 for a much larger range of frequencies.

## Specimen Size and Shape

Specimen size varied considerably in many previous experiments, depending on the parameters to be studied. Specimen sizes ranged from over 3000 $cm^3$ of concrete [11] to less than 100 $cm^3$ [6], with the smaller specimens generally being necessary for quick moisture conditioning while larger specimens were used for better representation of the concrete mass, for the study of age and mix design effects. Most of the studies used concrete prisms or cubes that, for the case of external electrodes, gave two even surfaces to apply the electrodes.

## Electrode Type

Table 1 shows that brass was the most common choice of electrode material for the studies reviewed. All other types of electrodes were also either metal or metallic coated (i.e., platinum black coating on hardened cement paste). For external-type electrodes plates, grids or meshes were used most commonly, while internal electrodes were normally wires or thin rods. Typically the internal electrodes were deformed by notching or knurling to insure a good bond with the cement paste. Other than the inherent difficulty in calculating resistivity from data collected using internal point or line electrodes, none of the studies showed any noticeably different trends that were considered the result of the electrode type. Internal electrodes have the advantage of being cast in place, which allows for quicker resistivity measurements as well as a constant contact zone.

## Method of Intimate Contact

Intimate contact, an expression used frequently in many of the studies reviewed, refers to the achievement of the best possible electrical contact between the concrete and the electrodes, or more accurately, the pore water system and the electrodes. Intimate contact allows for the actual resistance of the specimen to not be altered by additional resistance between the electrodes and the concrete. In general, at saturated conditions intimate contact with external electrodes is much easier to attain than at drier conditions as the water is removed from the contact zone first. One study [13] used five types of electrical cells, a group of three that used solutions of $Ca(OH)_2$ and steel plate electrodes and a group of two that used brass mesh electrodes. This latter group is of higher interest since it uses similar electrodes but two methods to attain intimate contact. The first method (Cell type C) involved simply placing the brass mesh electrodes on opposite ends of a specimen, while the second method (Cell type D) involved casting the brass meshes into the concrete specimens. A diagram of both methods of contact is shown in figure 13.

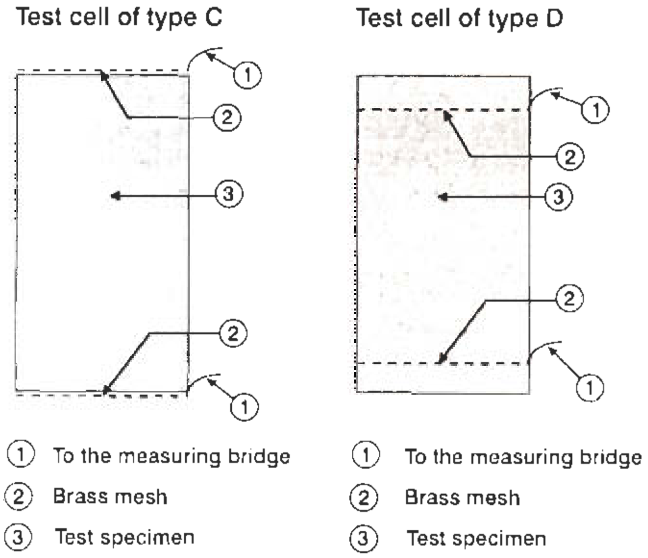

*Figure 13. Diagram of Test Specimens Using Different Methods of Contact, after Gjørv [13].*

A comparison of the results of these two methods of contact is shown in figure 11 [13]. The divergence of the resistance values below saturated conditions of the two similarly designed mixes shows that Cell type D is creating a higher degree of contact once the moisture has been removed, and furthermore that the degree of intimate contact is of decisive importance for resistance values in concrete tested at less than full saturation.

# 3 Experiments

## Specimen Description

It was decided for quick moisture conditioning and resistance stabilization to use a mature concrete with a water/cement ratio of 0.6 although a 0.4 mix was also available. The 0.6 concrete allowed for quicker equilibration at a given moisture level due to the coarser pore structure. The 0.4 concrete was used for a companion study of temperature sensitivity in the saturated state. The cement used for both mixes was a standard P30 cement (16 %, 59 %, 7.5 % and 10.4 % for $C_2S$, $C_3S$, $C_3A$ and $C_4AF$, respectively). The pertinent information of the two mix designs is shown in table 2.

**Table 2. Mix design information.**

| w/c | Cement (kg/m$^3$) | Silica Fume (% of cement) | Curing Type & Period | 90 Day Str. (MPa) |
|---|---|---|---|---|
| 0.6 | 350 | 0 | Wet 8 mo. | 48.8 |
| 0.4 | 390 | 4.9 | Wet 4 mo. | 71.4 |

Examination of the types of cells used previously suggested that, again for quick stabilization, specimens with a large surface area to volume ratio were necessary. All of the specimens for each water/cement ratio were cut from the same 5 cm thick slab. The specimens were approximately 10 cm x 5 cm x 2 cm. Precise measurements have been obtained to calculate specific resistance.

Fifteen specimens were prepared with 0.6 concrete, three parallels for each of five studies: temperature sensitivity at saturated condition, different degrees of saturation using stepwise desorption, and stepwise absorption from a 50 °C dry state using pure water as well as 3 and 6 % NaCl solutions. In addition, four saturated specimens of 0.4 concrete were prepared for a parallel temperature sensitivity study at saturated conditions.

## Measurement Type and Voltage

For this study a voltage of 0.9 volts and frequencies of 1 kHz and 120 Hz were used for resistance measurements. Upon comparison of data from both frequencies, it was discovered that the resistance measurements, although nearly identical at saturated conditions, deviated at lower moisture conditions, as is shown in figures 14 and 15, the latter of which shows that the ratio between the two measurements also changed with changing moisture content. Because of this phenomenon and the other evidence suggesting that 1 kHz and higher frequencies have greater stability, the remainder of the results will be expressed in terms of 1 kHz frequency and 0.9 Volt potential.

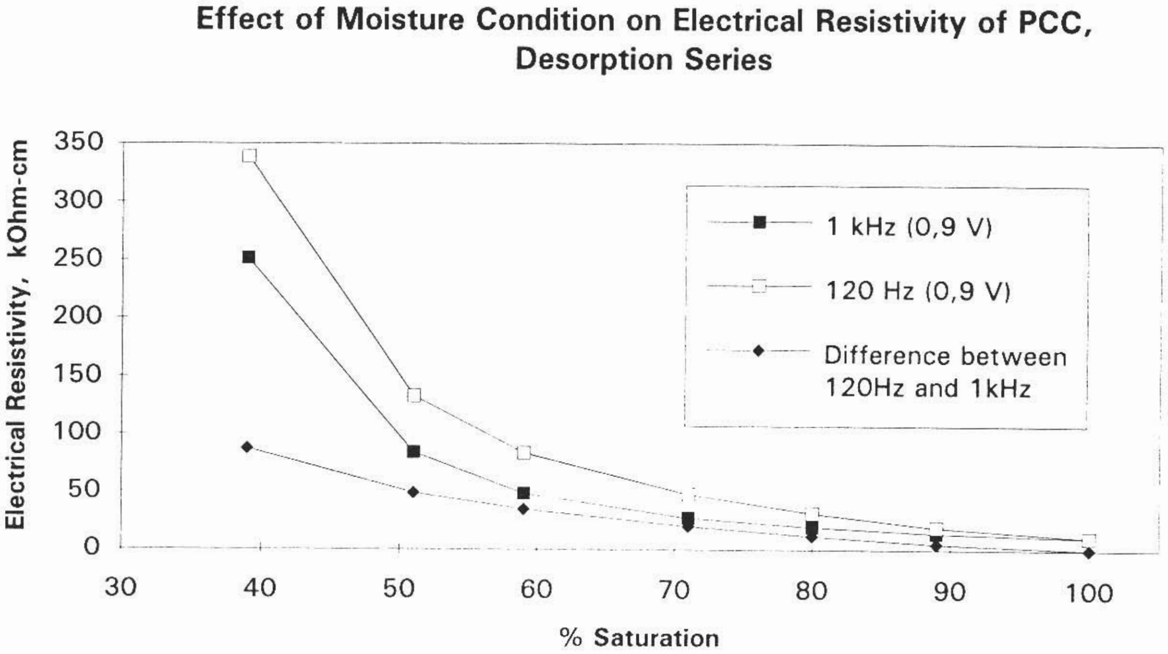

*Figure 14. Influence of Measuring Frequency on Electrical Resistivity of PCC at Various Moisture Conditions.*

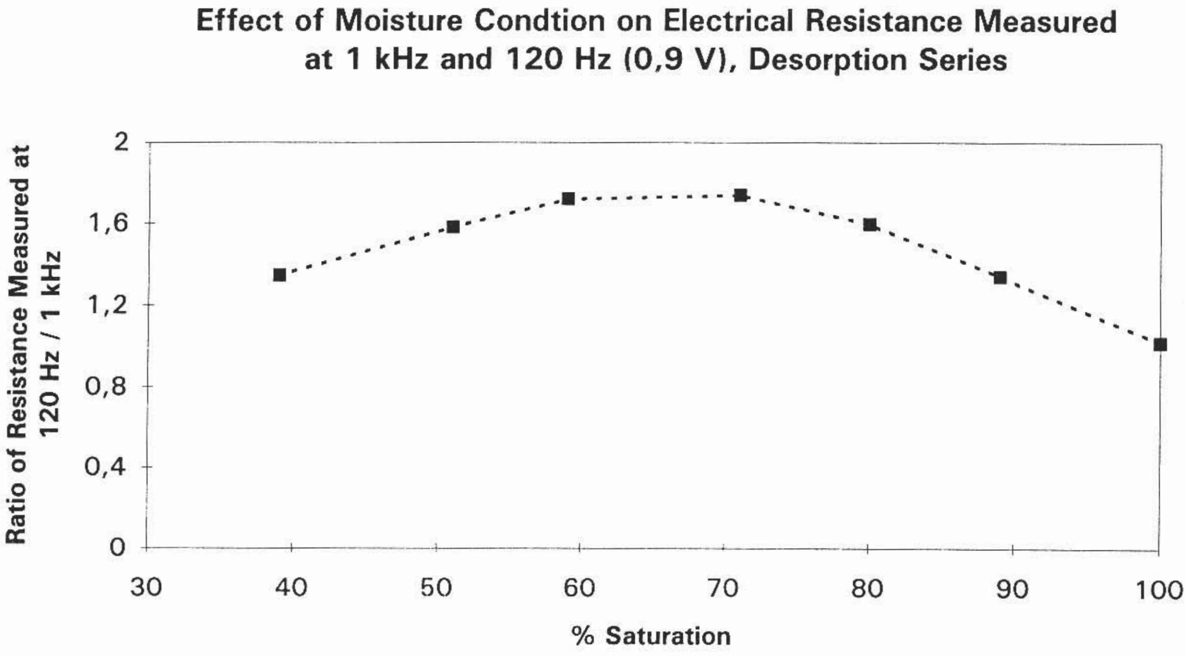

*Figure 15. Influence of Measuring Frequency on Electrical Resistance Measured at 1 kHz and 120 Hz (0.9 V).*

# Intimate Contact

As mentioned previously, various methods to attain intimate contact between the electrodes and concrete were used in other studies, from liquid cement paste to salt water. Since the specimens that were prepared for this study were to be tested at various moisture conditions, these water-based methods of contact were not usable and a method of dry contact needed to be found. The extreme importance of contact on the resistance results has been demonstrated in figure 11 [13]. Several types of metallic meshes, wools and foils were attempted, but it was learned that the amount of force that held the electrodes in place affected the resistance measured, with resistance decreasing with increasing force. In addition, once the outer film of water was lost on saturated specimens, resistance increased significantly with the loss of contact points. The method of brass meshes cast into the specimens allows for good contact, but as the specimens to be used for this study were already cast this was impractical.

The next attempted method of intimate contact was graphite paint of the type used in cathodic protection of concrete. There are several advantages to this method of contact: it is permanently fixed to the face of the concrete (allowing for quick measurement), the contact area is constant, and the moisture condition in the concrete can be controlled easily after the paint is cured. There is some increase in weight of the specimens due to the paint and leads; this was noted for each specimen and weights were adjusted.

The most important aspects of determining the acceptability of this method of contact were its reproducibility (consistency of results between identical specimens) and accuracy when compared to other accepted methods. Six saturated 100 mm cubes were prepared to study this aspect, as this size cube is generally accepted to be a large enough quantity of concrete to represent a mix; variation in results due to heterogeneity of the concrete should be small. Three of the cubes were 0.6 w/c concrete, while the other three were

0.4 w/c concrete. Two cubes from each set were prepared with the graphite paint electrodes, with two opposite sides painted on each cube and leads attached. The final cube from each set was tested with liquid electrodes, which simply involved saturating an absorbent pad with water from the same water bath that the specimens were stored. The resistances were checked in this saturated surface dry condition, and then were allowed to air-dry for 72 hours, after which the resistances were retested. Results from this study are shown in figure 16.

It is shown in figure 16 that resistance measurements taken using the graphite paint electrodes are not only reproducible, but compare favorably with the water electrode, suggesting that this is an acceptable method of contact. In fact, the graphite paint showed the least amount of change from the wet to the drier state. This is most likely due to the uneven drying due to the highly impermeable graphite paint. The contact with the moisture on these faces was not lost. Since there is no substantial divergence, unlike that shown previously in figure 11, this electrode type was considered adequate for the intended purpose. Thus, the specimens for use in the full studies were prepared with this electrode type, with the sides measuring 100 mm x 20 mm painted. A diagram of a typical test cell is shown in figure 17.

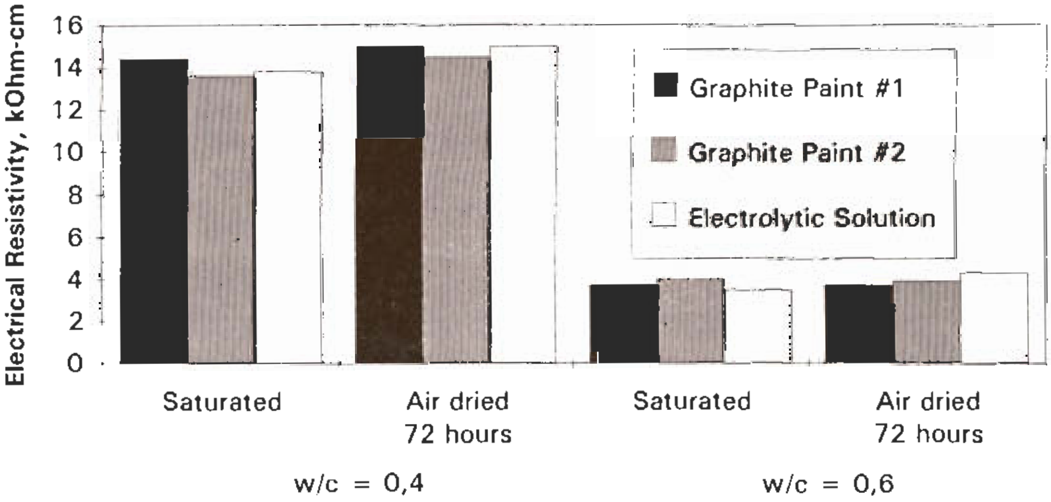

*Figure 16. Reproducibility of the Graphite Paint Electrode.*

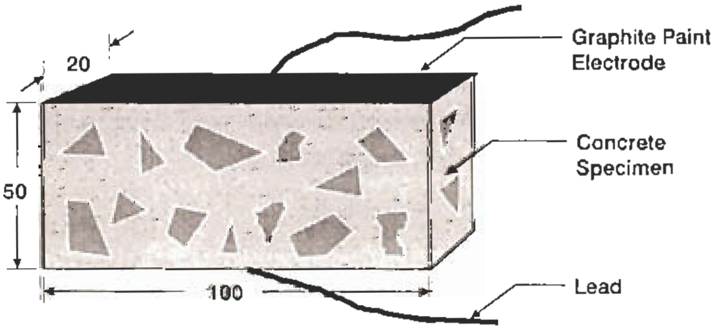

*Figure 17. Diagram of Typical Concrete Specimen Used for Electrical Resistance Studies (Dimensions in mm).*

## Resistivity Calculation

To determine resistivity from electrical resistance, precise measurements of the sample needed to be obtained. Three measurements were taken in each dimension for a representative average. The calculation of resistivity is:

$$R = \rho \cdot A_{ave}/L_{ave} \qquad \text{(Equation 3)}$$

where

$R$ is the resistivity (kOhm-cm)
$\rho$ is the resistance (kOhm)
$L_{ave}$ is the average distance between electrodes (cm)
$A_{ave}$ is the average cross section perpendicular to the electrodes (cm).

$L_{ave}$ was used for easy calculation. The distance between electrodes varied little so that the difference between $L_{ave}$ and the true effective path length was about 1 %. The true effective path length was found by simulating a concrete specimen as several parallel circuits with resistances reflecting the range of values measured for the distance between the electrodes.

## Moisture Conditioning

There were two separate series studied in this experiment, the desorption and absorption series. Specimens were conditioned by either stepwise drying from a saturated state or stepwise rewetting from a 50 °C dry state to attempt to define the outer edges of the hysteresis curve. An estimate for the moisture content of the specimens was obtained by drying three dummy specimens at 105 °C for twenty-four hours. This gave moisture contents of 5.7 %, 5.7 % and 5.8 % by weight of dry concrete. Thus, for preliminary calculation of moisture conditions, all specimens were assumed to have a saturated moisture content of 5.7 %. After completion of the experimental procedure, the specimens were dried at 105 °C for twenty-four hours to obtain the true saturated moisture content of each specimen, and moisture conditions were adjusted accordingly.

For desorption, the chosen method of drying depended on the degree of saturation needed. Drying from saturated conditions to 90 % and then to 80 % was accomplished by placing the samples in open air until the proper weight was achieved (0-3 days). To dry to lower moisture states, however, it was required to place the specimens in a 50 °C oven until the desired weight was achieved. It was felt that this temperature was low enough to prevent any pronounced drying cracks.

For absorption, the specimens were first dried at 50 °C to constant weight (approximately 14 days), and then conditioned by placing the specimens in a bath of either 0 %, 3 %, or 6 % NaCl until the next desired weight increase was reached. After the proper weights were attained, both absorption and desorption specimens were sealed in plastic and placed in a temperature controlled room for equilibration.

# 4 Results

Results are shown in figures 18 through 26. Figures 19 through 26 depict average values for both the equilibrium resistivity and, where applicable, the moisture condition of three specimens. As moisture conditions were not precisely calculated until after the testing procedure had been completed, estimates were occasionally different than actual saturation percentages and it was necessary to average the moisture condition along with the resistivity values. In addition, the temperature that the resistance measurements were taken varied from 15 to 18 °C, so all these measurements have since been normalized to 16 °C using the simultaneously collected temperature sensitivity data.

Except for the final resaturation stage of testing, specimens were considered at equilibrium when there was no change in electrical resistance between consecutive days or if any slight increase could be attributed to a change in the measured room temperature. Due to time constraints, for the final stage the resaturated specimens were removed before equilibrium was achieved, but all resistance values were believed to be less than 5 % from their final equilibrium values.

Figure 18 shows how the coefficient of variation (CV) among the parallel specimens changed with the moisture conditioning. Generally, the highest CV's occurred at very low percent saturation (under 40 %), indicating that the greatest differences occurred between specimens when the pore water system becomes discontinuous. Above 40 % saturation, however, it is shown that nearly all parallel studies had CV's of under 20 %. Thus, given the large amount of data, results will be presented without 95 % confidence ranges to clarify observed trends.

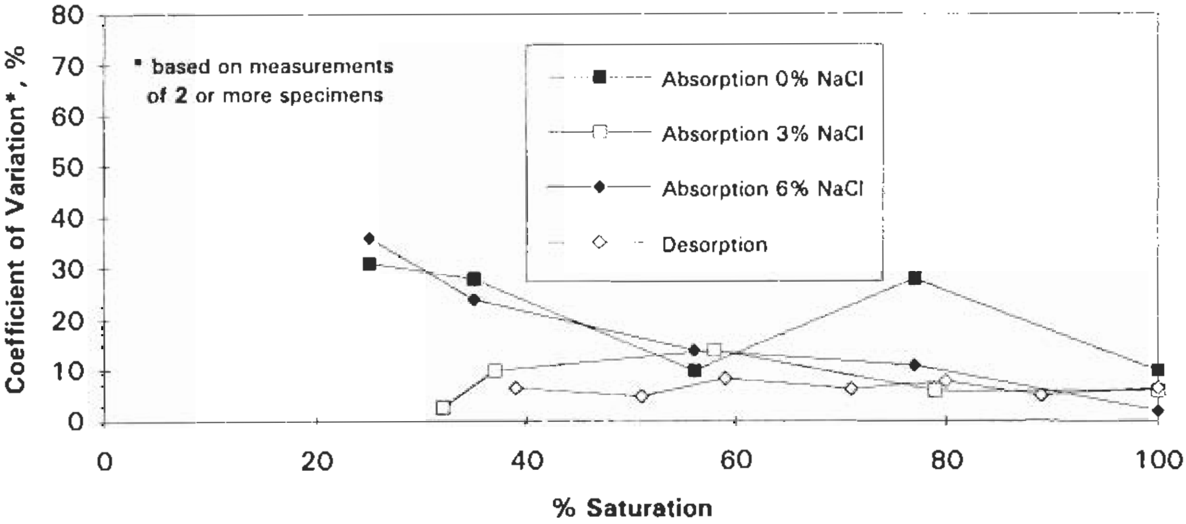

*Figure 18. Influence of Moisture Condition on Reproducibility of Electrical Resistance Measurements of PCC.*

# 5 Discussion of results

## Effect of Moisture Content

The electrical resistivity of concrete increases with decreasing moisture content. Figures 19 and 20 show that the effect of moisture content on electrical resistivity is large, with resistance increasing by orders of magnitude at low moisture contents. Figure 20 is plotted against a linear (rather than logarithmic) Y-axis to show that all the mixes showed a sharp change in the rate of resistance increase or decrease between 40-60 % saturation. This suggests the range where the pore water in the concrete begins to gain or lose continuity, resulting in more substantial change in the number of electrical flowpaths.

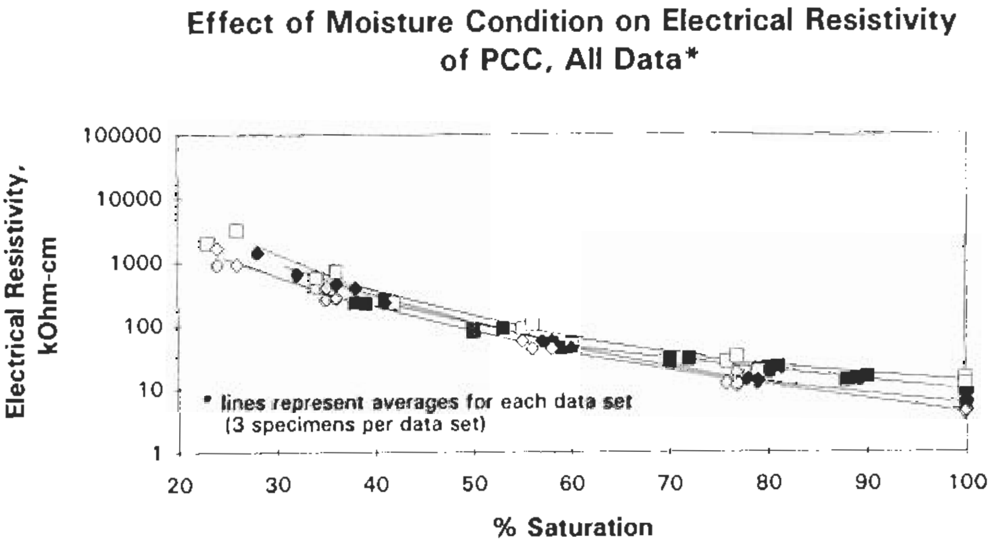

*Figure 19. Influence of Moisture Condition on Electrical Resistivity of PCC.*

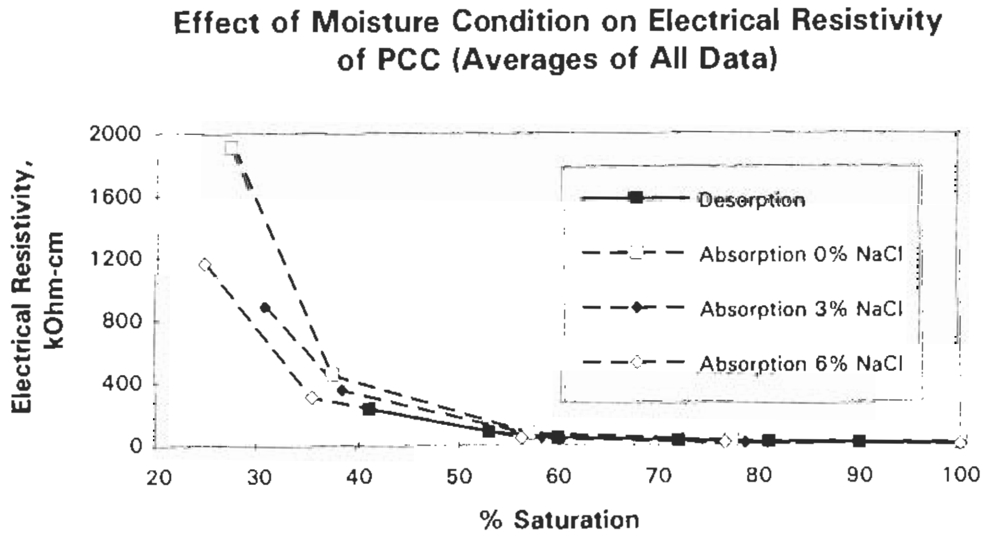

*Figure 20. Influence of moisture Condition on Electrical Resistivity of PCC.*

Figure 21 shows the effect of drying and rewetting on the saturated resistance levels. The comparison in this figure shows that, upon rewetting, resistances are higher than before conditioning. Generally it has been shown that, upon drying and rewetting concrete specimens, most parameters that indicate the relative continuity/discontinuity of the pore system (i.e., permeability, ice formation, chloride transport) suggest a more continuous pore system, so the electrical resistivity was also expected to decrease after this process. However, the resistance increased both for the desorption specimens and the specimens that absorbed pure water. We note that, as it was required to leave the specimens in a water (or salt) bath for a two week period, it is possible that ions were leached from the pore water system, increasing the measured resistance. Otherwise we have no explanation for this surprising result.

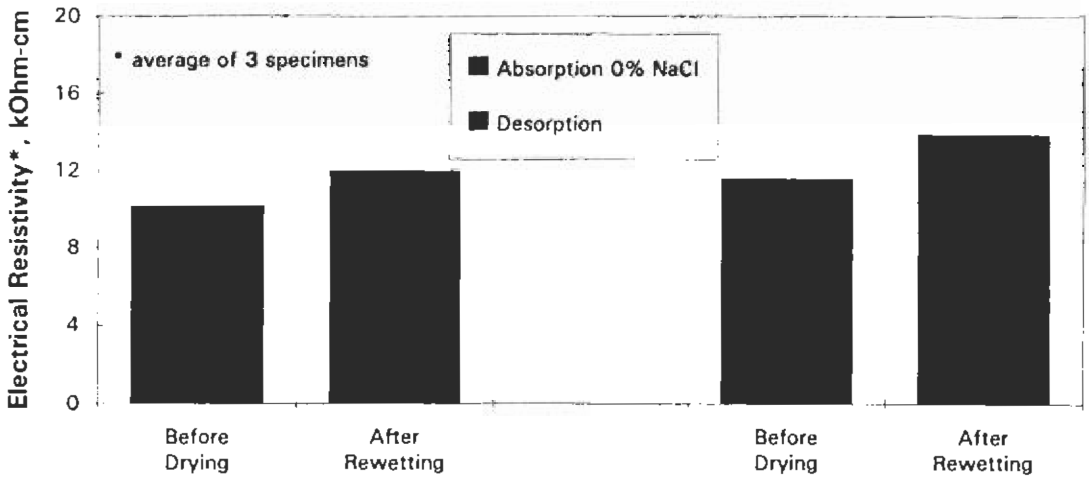

*Figure 21. Influence of Drying/Rewetting on Electrical Resistivity of Saturated PCC.*

## Effect of Temperature

Figure 22 shows a comparison of two concretes, 0.4 and 0.6 water-cement ratio, tested at various temperatures in saturated conditions. It shows that the effect of temperature (at levels above freezing) is near constant between these two mixes, with activation energy (A) values of approximately 2300 and 2450 for 0.6 and 0.4, respectively, both of which

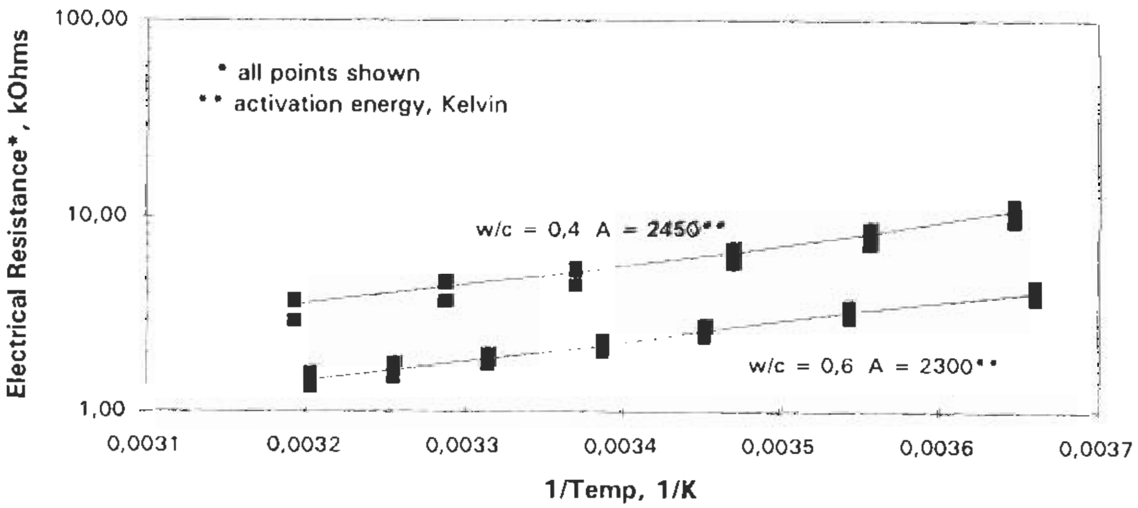

*Figure 22. Influence of Temperature on Electrical Resistance of Saturated PCC.*

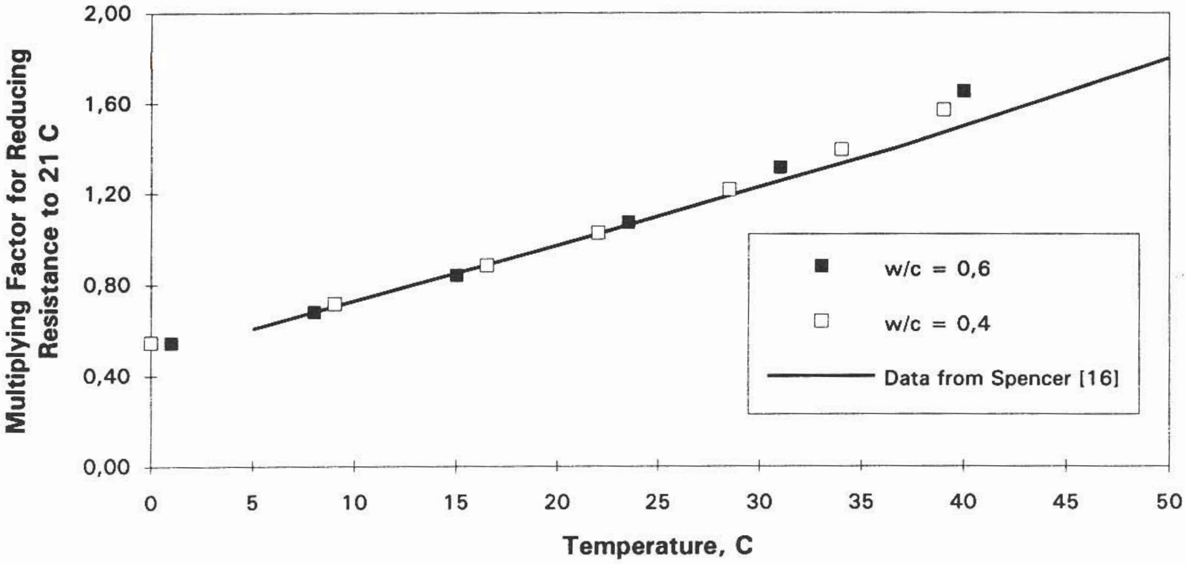

*Figure 23. Temperature Reduction Curve.*

correspond with approximately 3 % change per degree C at 21 °C. The data, plotted against the graph by Woefl and Lauer in figure 23, also agrees with the three previous studies suggesting that, at saturated conditions, the pore water's temperature sensitivity is independent of mix design.

Measurements of resistance at several different temperatures at each moisture condition were also made, as indicated earlier, and values for the activation energy were calculated. These values are shown in figure 24, *with higher A values indicating increased sensitivity* to temperature. This figure suggests that the sensitivity to temperature is related to the degree of saturation, with decreasing degrees of saturation resulting in increased sensitivity to temperature. Under 30 % saturation, for example, the activation energy

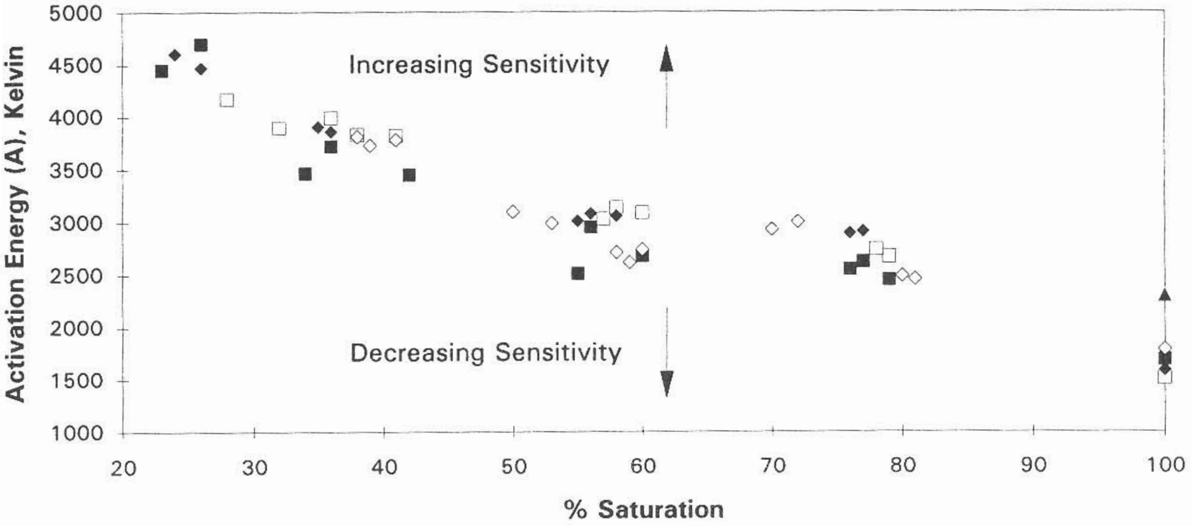

*Figure 24. Influence of Moisture Condition on Temperature Sensitivity of Electrical Resistivity of PCC.*

calculated corresponds to a sensitivity of about 5 % per degree C at 21 °C, whereas above 70 % the sensitivity is about 3 % per degree C. This creates a second order problem when both moisture content and temperature are varying, as moisture content affects the temperature sensitivity as well as the electrical resistivity of concrete.

The activation energies calculated from the desorption and absorption series at fully resaturated conditions show a sensitivity that is lower than the trend lines would indicate. This is possibly due to a laboratory error (i.e., the resistances were recorded before thermal equilibrium was reached). Also shown in figure 24 is the A value for the 0.6 w/c saturated specimens used for the initial temperature study (see figure 22) which, at a value of 2300, falls in the anticipated range.

## Effect of Chlorides

The stabilization of the concrete resistance after suction of a given amount of liquid is shown in figure 25. It should be noted that, for all of the specimens (desorption or absorption), stabilization always involved an increase in resistance over time, with an average time to stabilization at 15 °C of about two weeks. This is most likely not due to loss of moisture to the air, as initial and final weights (after equilibration) were usually identical. For pure water the equilibration process was relatively rapid. However, increasing levels of NaCl in the liquid slowed the process of stabilization. This suggests at least two possible mechanisms are involved in the stabilization process: first, redistribution of the liquid from the surface throughout the pore system and, second, dissolution of ions crystallized in the pores and chemical binding of the chloride ions. The latter process appears to slow the total equilibration process.

The increase in resistance during the equilibration period appears logical when considering the process involved. When water is either added or removed from the concrete pore system, the previous equilibrium condition is changed to two relatively "wet" and "dry" zones, with the wet zone being near the surface for the absorption series

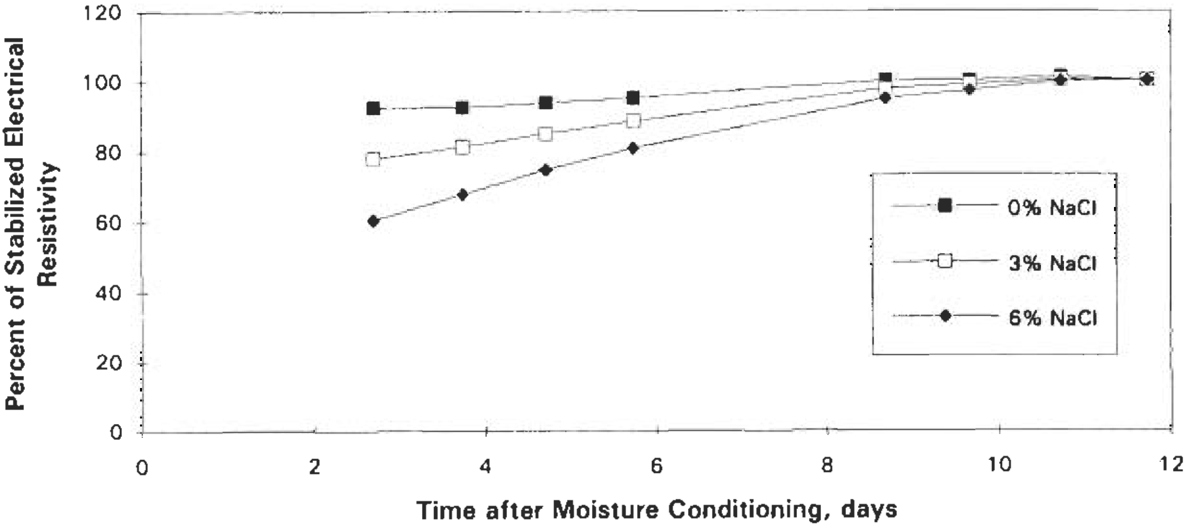

*Figure 25. Influence of Chloride Absorption on Equilibration Time of Electrical Resistivity of PCC.*

and near the core for the desorption series. At that time the wet zone conducts most of the electrical current through its relatively continuous pore water system. Migration of the pore water to the dry zone during equilibration results in a loss of continuity in the wet zone. It is believed, although the total moisture content has remained unchanged, the smaller, continuous wet zone in concrete conducts better than the full concrete body with moisture equally distributed. A similar gradual increase in resistance was noticed when the concrete specimens were returned to fully saturated conditions, which does not agree with this theory. As noted earlier, it is possible that ions were leached from the pore water system during the lengthy resaturation process, which could explain this gradual increase.

Figure 26 shows that the effect of chlorides becomes more pronounced when compared to pure water as the degree of saturation increases. This is most likely due to the increased amount of salt water relative to the unaltered pore water that remained in the pore system after 50 °C drying. This figure also shows that, for a given moisture condition, the chloride concentration has little effect on the resistivity. This is a surprising result with the implication that the final ionic concentration of the pore water solution is the same for both initial chloride concentrations. This trend is similar to that seen by Gjørv and Monfore for chlorides added to the mixwater (see figure 9), where above a certain concentration of chlorides added the decrease in electrical resistance was small.

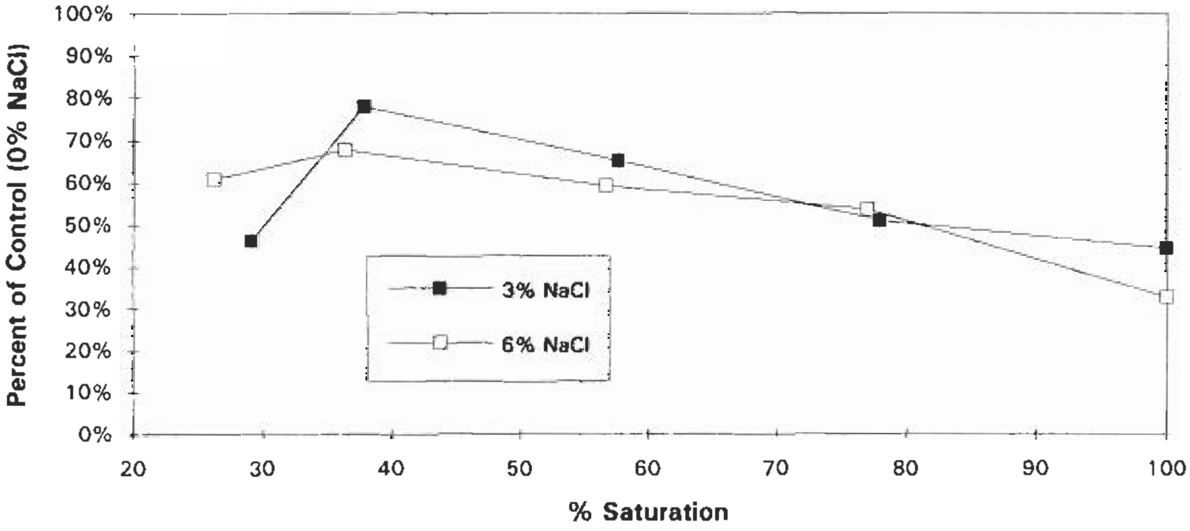

*Figure 26. Influence of Chlorides on Electrical Resistivity of PCC.*

# 6 Conclusions

From this investigation of electrical resistance in concrete, the following conclusions can be drawn:

1) Moisture content greatly affects the electrical resistance in concrete. For high moisture contents the rate of change is constant or only slightly increasing, but in the range of 60 to 40 % (presumably where continuity of the pore liquid begins to disappear) the rate of resistance increase rises sharply. From 40 % to 100 % degree of saturation, the range of concrete resistivity for a 0.6 water/cement ratio and no additional chlorides is approximately 250 kOhm-cm to 10 kOhm-cm.

2) Temperature affects the electrical resistivity in concrete. At saturated conditions a rate of 3 % change per degree C (at 21 °C) was found, with resistance decreasing with increasing temperature. At lower degrees of saturation, however, this sensitivity increased, with a value of approximately 5 % per degree C at 25 % saturation.

3) The addition of chlorides into the pore water system decreased the resistance substantially, with the effect increasing at higher levels of saturation. At saturated conditions, electrical resistivity for concrete with pore water containing 6 % NaCl was less than 40 % than that of concrete with no additional chlorides. The difference between 3 % and 6 % NaCl pore water was surprisingly low, however. No apparently significant difference was noticeable between the two chloride concentrations.

The influence of frequency varied. A previous study examined (see figure 12) showed a resistance at 1 kHz of only 85-90 % of that observed at 100 Hz. This study also showed a similar level of sensitivity at saturated conditions, but that changed as the concrete was dried (see figure 15). At 60-70 % saturation the resistance measured at 1 kHz to be approximately 60 % of that observed at 120 Hz, while at 40 % saturation it was nearly 80 % again. We note that, except for the temperature study at saturated conditions, all of the presented results are for concrete with w/c = 0.6, and the conclusions are therefore limited.

# 7 Practical consequences

The purpose of this study was to evaluate the applicability of electrical resistance measurements on in-situ concrete to monitor changes in moisture content. Other than the differences which come from mix design differences (i.e., w/c-ratio, silica fume, curing temperature), this study focused mostly on environmental factors: temperature, chloride concentration, and moisture content. Now quantified, the influence of each of these parameters on field concrete needs to be discussed.

The small amount of Norwegian field data on concrete moisture contents suggest that the degree of saturation (DS) at least 20 mm from an exposed vertical surface is unlikely to be less than 70 %. Thus, the range from 70 to 100 % saturation is of particular interest. Figure 27 shows a "blowup" of the resistance-degree of saturation curve (figures 19 and 20) in this range. Above about DS = 70 % the rate of change is close to linear for the four data sets with a slope of about 3 % change in resistance per 1 % degree of saturation. Below this range the slope increases sharply.

In the same DS range of 70 to 100 % the temperature sensitivity has been shown earlier to be about 3 % change in resistance per °C. Consequently a very accurate temperature record is required at the same location where the resistance is measured, if a resistance change is to be interpreted in terms of moisture change.

The influence of chlorides is, as already presented, quite large, but by no means linear. A 3 % (or 6 %) NaCl solution in the pores cuts the resistance by a factor of about 2.

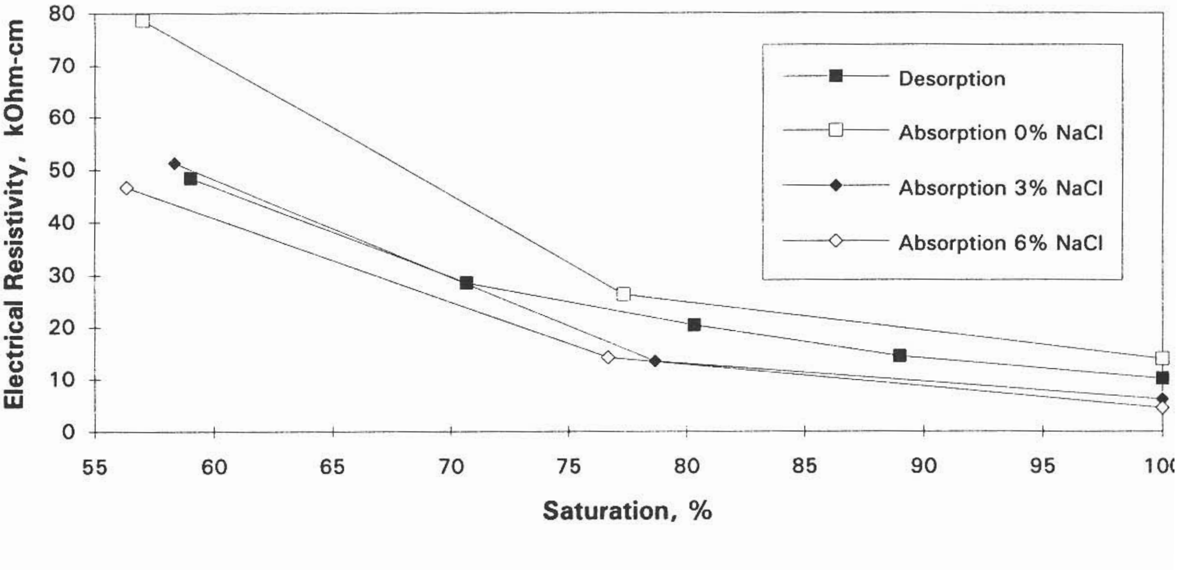

*Figure 27. Influence of Moisture Condition on Electrical Resistivity of PCC for High Moisture Conditions.*

More work is definitely needed on the effects of chlorides. However, chlorides normally penetrate slowly into the concrete. Thus, over a shorter term, the chloride concentration a bit inside an exposed surface probably can be assumed constant. Then, according to figure 27, the slope of resistance vs. degree of saturation may possibly be assumed to hold regardless of chloride content. Interpretation of resistance changes in terms of changed degree of saturation of course still presupposes very accurate temperature data.

**In summary:**

Exposed coastal concrete structures in Norway appear to have quite high moisture contents: in the range of 70 to 100 % degree of saturation.

In this DS range the resistance of the concrete changes roughly as follows:

- 3 % per °C temperature change
- 3 % per % change in degree of saturation, and
- 50 % due to the ingress of chlorides.

This is a slow process and the chloride content may possibly be assumed to be constant over short periods.

Even a rough monitoring of changes in moisture content in field concrete by means of resistance measurements require accurate simultaneous temperature monitoring.

# 8 Recommendations

The following recommendations for the measurement of electrical resistivity in concrete are offered:

1) For measurement of electrical resistivity, alternating current at a frequency of at least 1000 Hz is recommended to minimize differences in resistance measurements due to voltage level. Further study should be performed to explain the changing difference between electrical resistivity readings at 1 kHz and 120 Hz with changing degree of saturation.

2) For measurement of electrical resistivity with the emphasis on determining moisture content, simultaneous temperature measurements must be carried out to eliminate the creation of a second order problem, as moisture content not only affects the resistivity but also the temperature sensitivity of the resistivity.

3) Further work should be performed to explain the increase in electrical resistance after drying and resaturation, which is in contradiction to other concrete measurements (i.e., permeability, chloride transport), as well as to explain the gradual increase in resistivity with time after water absorption.

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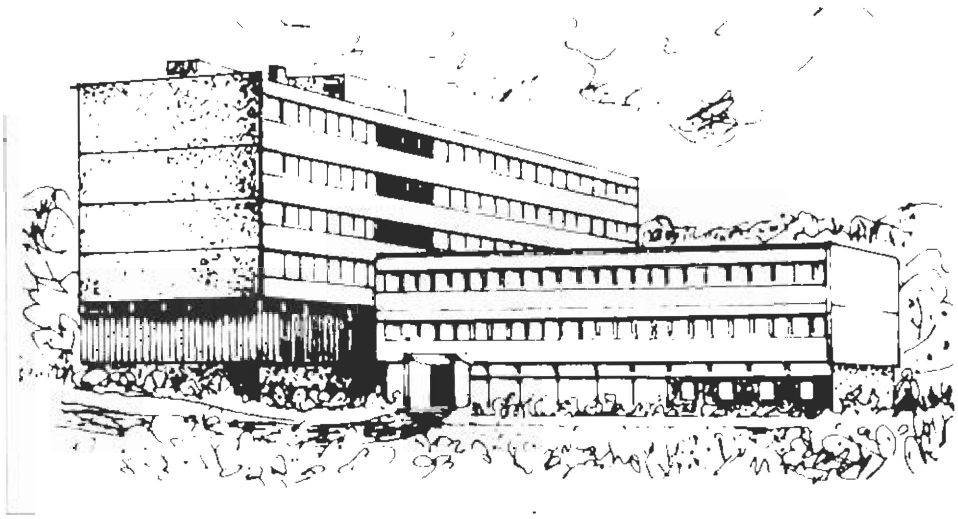

# The Norwegian Road Research Laboratory

## Organization

The Norwegian Road Research Laboratory (NRRL) was established in 1938 and is a department in the Directorate of Public Roads. The NRRL is organized in five technical sections, **Bituminous materials and Chemistry**, **Concrete**, **Geology**, **Pavement design**, and **Soil mechanics**, as well as a secretariat.

## Field of operation

The main activities of the NRRL are Research and development, Exploration and design, Specification and guidelines, Information and training, and Administrative duties on behalf of the Directorate of Public Roads.

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