Review and Evaluation of Techniques for Measurements of Concrete Resistivity

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ABSTRACT

The electrical resistivity method is increasingly being employed as a non-destructive technique to evaluate the chloride permeability of concrete. Various test methods and resistivity meters have been developed for measurements of concrete resistivity. However, as the test method and specimen geometry may have a significant effect on the measured resistivity, the resistivity values measured with different methods and different models of resistivity meters are usually not comparable. In addition, concrete resistivity is sensitive to other factors, e.g. temperature, moisture content, etc. In this paper, the different techniques and different models of meters for resistivity measurements are introduced. The resistivity values measured using different techniques and several models of resistivity meters are compared by converting the measured values to the bulk resistivity values. It is found that bulk resistivity values from different test methods or different models of resistivity meters are consistent. In addition, it was also found that the resistivity measurements according to the Wenner method could be possibly performed by taking four readings at 90 degree internals instead of eight readings without reducing the accuracy or precision of the measurements.

INTRODUCTION

Measuring the electrical resistivity of water-saturated concrete has been employed as a non-destructive method to evaluate the chloride permeability of concrete in several standards[1, 2]. These electrical resistivity methods were developed based on the correlation between concrete resistivity and the charge passed through the rapid chloride permeability (RCP[3]) test [4]. More recent investigations show that concrete resistivity is also correlated to chloride diffusion coefficients [5].

Compared with other methods, the electrical resistivity method is easy, fast and non-destructive, which makes it being accepted by state agencies and Department of Transportations (DOTs) in the USA. Also, several new models of resistivity meters have been developed in recent years and some of the old models are no longer manufactured. Therefore, it is necessary to evaluate and compare the resistivity values measured from different resistivity meters and thus provide basic information for transportation agencies and DOTs to select and approve the meters used for concrete resistivity measurements.

METHODS FOR RESISTIVITY MEASUREMENT

The two-plate method for measuring bulk resistivity and the four-electrode (Wenner) method for measuring the surface (or apparent) resistivity are the two most widely used methods to measure concrete resistivity.

Two-Plate Method

The two-plate method is a direct method to measure the bulk resistivity of concrete. Two electrically conductive plates are attached to the two ends of concrete and the electrical resistance between two plates is measured, as shown in FIGURE 1.

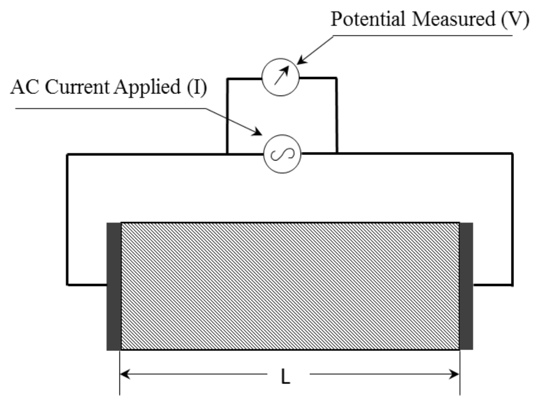


FIGURE 1 Illustration of two-plate method.

The bulk resistivity is then calculated with the following equation:

$$\rho = \frac{V}{I} \times \frac{A}{L} \tag{1}$$

where A is the cross-section area and L the length of the specimen. The two-plate method is usually not affected by the geometry of the specimens, e.g. cylinders or rectangular prisms. To reduce the effect of polarization from direct current (DC), an alternating current (AC) is usually applied.

Although various models of resistivity meters have been developed according to the two-plate method, there is not an existing standard which specifies the use of this method to measure concrete resistivity. A similar method has been recently published in ASTM C1760 [6]. This method uses the same setup as ASTM C1202 [3] by applying a direct voltage of 60V to measure the bulk conductivity (or resistivity). Recently, a round robin test was performed using the two-plate method and the results of the investigation have led to a drafted standard for bulk resistivity measurement [7].

The disadvantage of the two-pate method is that the measured resistivity value can be easily affected by the contact between the plate and concrete. A large resistance may appear if the plate is not properly attached to the surface of the concrete. To eliminate or reduce this effect, electrically conductive gels or a sponge (or paper and cloth) saturated with conductive solutions (e.g. lime water) are usually applied between the plate and concrete surface. In addition, the two-plate method is not practical to measure the resistivity of on-site structures due to the size and geometry of the structures and presence of rebar. However, the resistivity of on-site structures can be obtained by measurements performed on drilled cores.

Four-Electrode (Wenner) Method

The four-electrode (Wenner) method is a well-established method employed in AASHTO TP-95-11 [1] and FM 5-578 [2]. This method is designed by putting four equally spaced electrodes on the surface of concrete. An alternative current is applied through the two external electrodes and the resultant potential between the two internal electrodes is measured, as shown in FIGURE **2**.

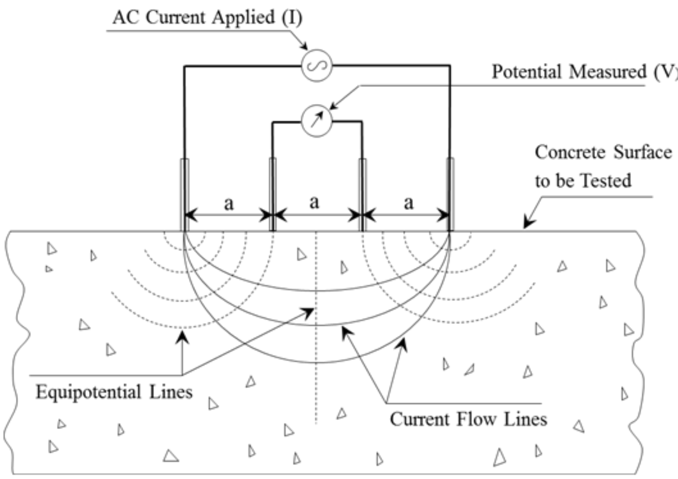


FIGURE 2 Illustration of the four-electrode (Wenner) method.

If the measured concrete is semi-infinite, the electrical resistivity is calculated as:

$$\rho = \frac{2\pi a V}{I} \tag{2}$$

Most tested specimens have limited dimensions (e.g. 10×20 cm cylinder), therefore, the measured resistivity value displayed on the resistivity meter is the apparent (also named as measured or surface) resistivity (ρ_{app}) rather than the bulk resistivity. The apparent resistivity is affected by factors such as the geometry of the specimens, the presence of rebar, the electrode spacing as well as the measurement location. Therefore, different apparent resistivity values may be obtained on the same concrete specimen if the measurement is performed with different electrode spacing and/or at different locations. To overcome this problem, the AASHTO TP95-11 and FM 5-578 have specified a routine measurement procedure by performing resistivity measurements on concrete specimens of standard sizes (e.g. 4×4in. or 10×20cm cylinders) with a fixed electrode spacing (i.e. 1.5 in. or 3.8 cm) and reporting the measured surface resistivity value. Therefore, the resistivity values used in the AASHTO and Florida methods to classify chloride permeability are apparent resistivity values rather than bulk resistivity values. The selection of the apparent resistivity in these methods is to avoid the unnecessary complications for the users to convert the apparent resistivity to bulk resistivity.

The resistivity values measured using the two-plate method and the Wenner method can be compared by converting the apparent resistivity value to bulk resistivity value using a geometry cell constant:

$$\rho = \frac{\rho_{app}}{K_g} \tag{3}$$

The cell constant K_g is dependent on the specimen size/geometry, electrode spacing, measurement location and even presence of rebar. The converted bulk resistivity values can then be compared with the values obtained from the two-plate method. The K_g value can be obtained by modeling using the finite element method (FEM). FIGURE **3** shows the geometry cell constants for 4×8 in. (10×20 cm) cylinders according to the measurement procedure of AASHTO TP 95-11 or FM 5-578. With the geometry factor (K =1.89 for a=3.8 cm) presented in FIGURE **3**, the apparent (surface) resistivity values used in AASHTO TP 95-11 or FM 5-578 can be converted to bulk resistivity values, thus the resistivity values measured by the two-plate method can be used directly to evaluate the chloride permeability of concrete. TABLE 1 presents the evaluation of chloride permeability using apparent and bulk resistivity values.

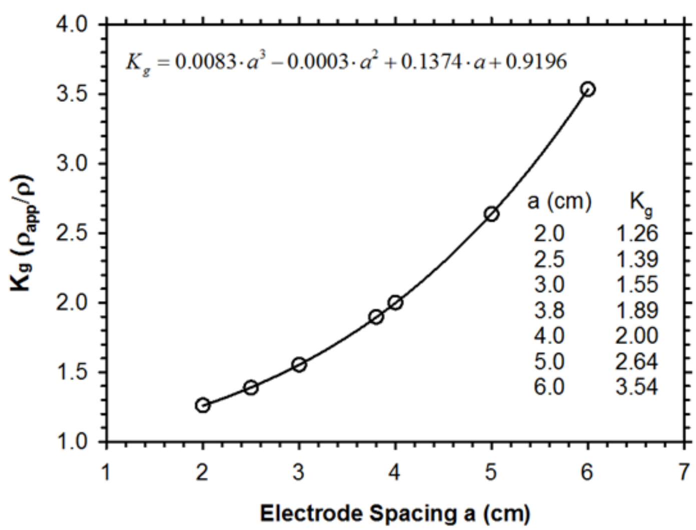


FIGURE 3 Geometry cell constant for 4×8 in. (10×20 cm) cylinder [8].

TABLE 1 Correlation between Chloride Permeability and Concrete Resistivity[2, 8].

Chloride Ion Penetration	RCP test Charge Passed (coulombs)	Surface Resistivity (kΩ cm) 10×20cm Cylinder a=3.81cm	Bulk Resistivity (kΩ cm)
High	>4,000	< 12	< 6.3
Moderate	2,000−4,000	12 – 21	6.3 – 11
Low	1,000−2,000	21 – 37	11 – 20
Very Low	100−1,000	37 – 254	20 – 134
Negligible	<100	> 254	> 134

OTHERS FACTORS AFFECTING RESISTIVITY MEASUREMENT

Degree of Saturation

The degree of saturation of the specimens has a significant effect on the measured resistivity. The AASHTO and Florida standards specify to perform resistivity measurement on saturated specimens which are cured in a moist room with 100% relative humidity (RH) or in saturated lime water. For specimens under un-saturated condition, it is suggested to immerse the specimen in water until full saturation or to saturate the specimens by a vacuum pump as indicated in ASTM C1202 [3].

Presence of Rebar

When resistivity measurement is performed on on-site structures using the Wenner method, the presence of rebar is often not avoidable. As the rebar is much more conductive than concrete, it can significantly affect the measured resistivity. Prior to the measurement, a rebar locator is necessary to locate the rebar. The effect of rebar can be reduced by performing resistivity measurements far from the rebar [9]. Finite element modeling (FEM) shows that the effect of rebar can also be minimized by placing the probe perpendicular to the direction of the rebar [10]. The modeling results show that for concrete with rebar diameter of 16mm and concrete cover of 5cm, the effect of rebar is less than 2% if the measurement is performed with the probe on top and in perpendicular direction of the rebar [10].

Temperature

The temperature of the concrete at which resistivity measurement is performed has a significant effect on the measured resistivity. The correlation between temperature and concrete resistivity has been found to follow Arrhenius law and the activation energy for resistivity was found to be dependent on the resistivity of concrete [11]. The following equation has been proposed to normalize the measured bulk resistivity values to the values at 21°C [11]:

$$\rho_{21} = 10 \cdot \exp\left[\frac{\ln\left(10/\rho_T\right)\cdot T + 273.15\cdot\ln\left(10/\rho_T\right) - 3.98755\cdot T + 83.7385}{0.54312\cdot T - 305.556}\right] \tag{4}$$

where ρ_{21} (kΩ cm) is the bulk resistivity at 21°C, and ρ_T (kΩ cm) is the measured bulk resistivity at temperature T (°C).

COMMERCIALLY AVAILABLE RESISTIVITY METERS

Giatec RCON™ Resistivity Meter

Giatec RCON™ Resistivity Meter, as show in FIGURE 4, is designed according to the two-plate method to directly measure the bulk resistivity of concrete cylinders. Unlike most other meters, this meter has adjustable AC current frequency (1 to 30 kHz). More accurate measurements can be obtained by adjusting the current frequency.

FIGURE 4 Giatec RCON™ Resistivity Meter for measurement of bulk resistivity of concrete.

Merlin Bulk Resistivity Meter

The Merlin bulk resistivity, as shown in FIGURE **5**, is designed according to the two-plate method. It is designed to measure the bulk resistivity of 10×20 cm (4×8 in) water saturated cylinders or cores. The meter uses an AC current with a frequency of 325 Hz.

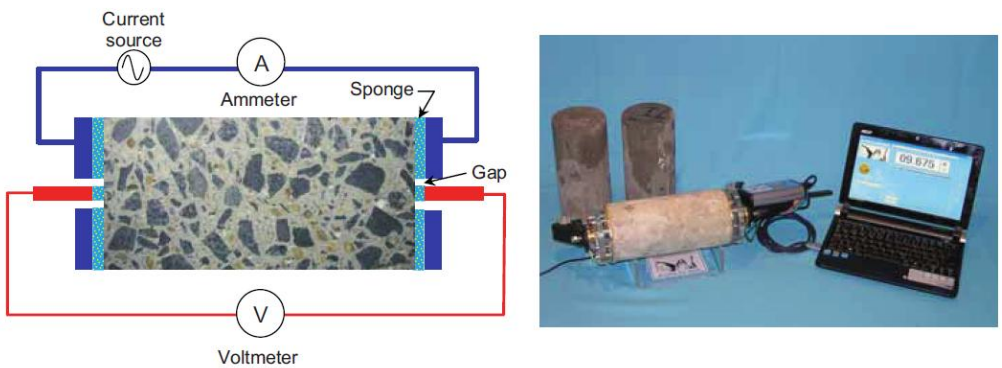


FIGURE 5 Merlin bulk electrical resistivity meter.

CNS FARNELL Resistivity Meter

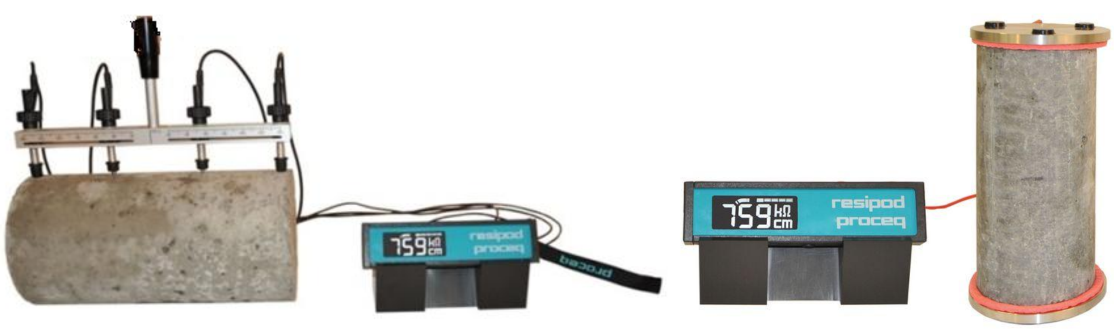
CNS FARNELL Resistivity Meter was one of the earliest commercial meters in the market for measuring concrete resistivity, as shown in FIGURE **6**. It is designed according to the Wenner method with adjustable electrode spacing from 2cm to 7cm. The AC current frequency used in this meter is 13 Hz. This was the meter used by FDOT to develop the earliest resistivity method (FM 5-578) to characterize the chloride permeability of concrete and to replace the RCP test. The CNS FARNELL Resistivity Meter is now obsolete and has been replaced by the Proceq Resipod resistivity meter when Proceq Corporation bought CNS Farnell.

FIGURE 6 CNS FARNELL resistivity meter.

Proceq Resipod Resistivity Meter

The Proceq Resipod resistivity meter, as shown in FIGURE **7**, is a successor of the CNS FARNELL resistivity meter. Compared with the FARNELL resistivity meter, the Resipod meter has a much smaller size and the measured data can be recorded and exported to a computer. In addition, the AC current frequency of the Resipod meter is 40 Hz. The Resipod meter has two models with electrode spacing of 3.8 cm (1.5 in.) and 5 cm (2 in.), respectively. The 3.8 cm spacing model is specially designed to comply with AASHTO 95-11.

FIGURE 7 Proceq Resipod resistivity meter.



(a) **(b)**

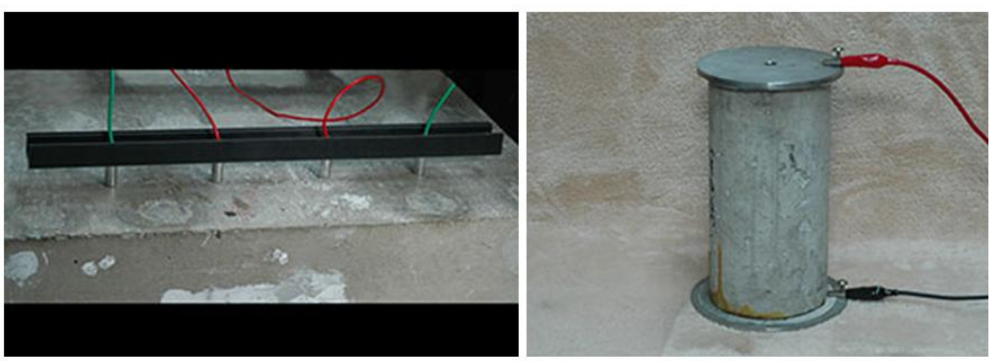
FIGURE 8 Proceq Resipod resistivity meter connected with a probe with adjustable electrode spacing (a) and with a bulk resistivity kit (b).

A probe with adjustable electrode spacing is also designed to measure concrete specimens with large sizes, as shown in FIGURE **8**(a). Additionally, a Resipod Bulk Resistivity kit is available which is designed in conjunction with the Proceq Resipod resistivity meter to measure the bulk resistivity of concrete cylinders, as shown in FIGURE **8**(b). This Bulk Resistivity kit can also be used in conjunction with the CNS FARNELL resistivity meter. With this method, a procedure is required to convert the measured resistivity value displayed on the meter to the bulk resistivity value of the concrete [7].

Resitest-400 Resistivity Meter

The Resitest-400 resistivity meter is designed according the Wenner method. The old model of this meter had a fixed electrode spacing of 5cm, as shown in FIGURE **9**. The recently developed model of this meter has a fixed electrode spacing of 3.8 cm and 5cm. The probe with 3.8cm electrode spacing was designed to comply with AASHTO TP 95-11. Accessories also have been developed to measure apparent resistivity with variable electrode spacing or to measure the bulk resistivity, as shown in FIGURE **10**.

FIGURE 9 Resistest-400 resistivity meter.



(a) (b)

FIGURE 10 Accessories used to measure apparent resistivity with variable electrode spacing (a) and bulk resistivity (b) in conjunction with the Resistest-400 resistivity meter.

Giatec Surf™ Resistivity Meter

The Giatec Surf resistivity meter was designed according to the Wenner method with electrode spacing of 1.5 in (3.8 cm), as shown in FIGURE 11. This meter has adjustable AC current frequency of 10 to 100 HZ and is designed specially to comply with AASHTO TP 95-11. A holding device is designed with four sets of electrodes (located at 90 degree intervals) which make the measurements much easier and faster without rotating the specimens. The average of the measurements is calculated automatically and displayed on the meter. Also, this device can mitigate the water evaporation during the measurements.

FIGURE 11 Giatec Surf™ resistivity meter.

EVALUATION OF RESISTIVITY METERS

Four resistivity meters were evaluated in this investigation, which included Resipod meter with 3.8 cm spacing (Wenner method), Resipod meter with 5 cm spacing (Wenner method), Resitest-400 meter with 5 cm spacing (Wenner method) and the RCON meter (two-plate method). Fourteen 4×8 in. (10×20 cm) concrete cylinders from fourteen different mixtures were used. The concrete mixtures include OPC concrete and concrete with different type/replacement ratio of mineral admixtures. The bulk resistivity of the cylinders ranged from 5 kΩ cm to 200 kΩ cm. To compare the measured resistivity values from different meters, all the measured apparent resistivity values were converted to the bulk resistivity values using the corresponding geometry cell constant values presented in FIGURE **3**.

Comparison of the bulk resistivity values obtained from different resistivity meters is present in FIGURE **12**. It shows that, after converting the apparent resistivity values to bulk resistivity values, consistent bulk resistivity values were obtained using different meters. In some cases, the bulk resistivity value obtained from the RCON meter was slightly higher than the values obtained with other meters, which is possibly attributed to the resistance caused between the concrete surface and the plates. However, the bulk resistivity values obtained from the Wenner methods showed excellent consistency.

FIGURE **13** shows a more detailed comparison between the bulk resistivity values obtained from different meters, in which the bulk resistivity from the Resipod meter with 3.8 cm spacing was used as the reference. A good correlation was obtained and the difference between the bulk resistivity values obtained from other meters and the reference meter (Resipod-3.8 cm spacing) is within 4%. The results indicate that all the evaluated meters can provide resistivity values with acceptable accuracy.

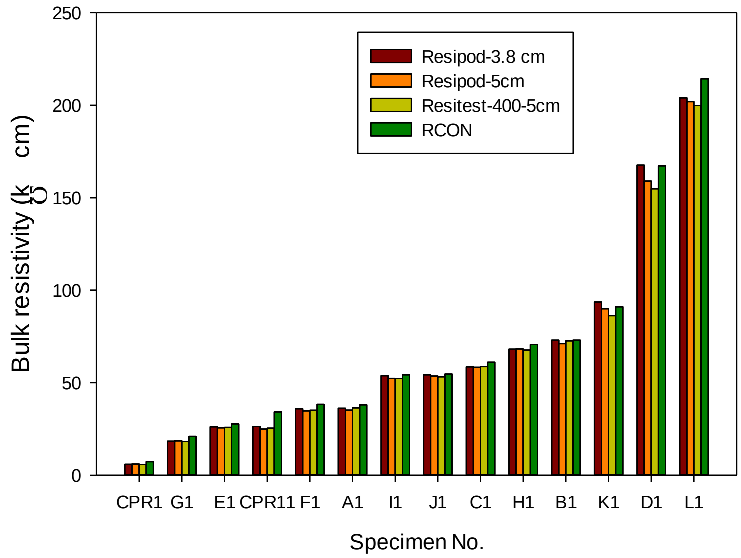
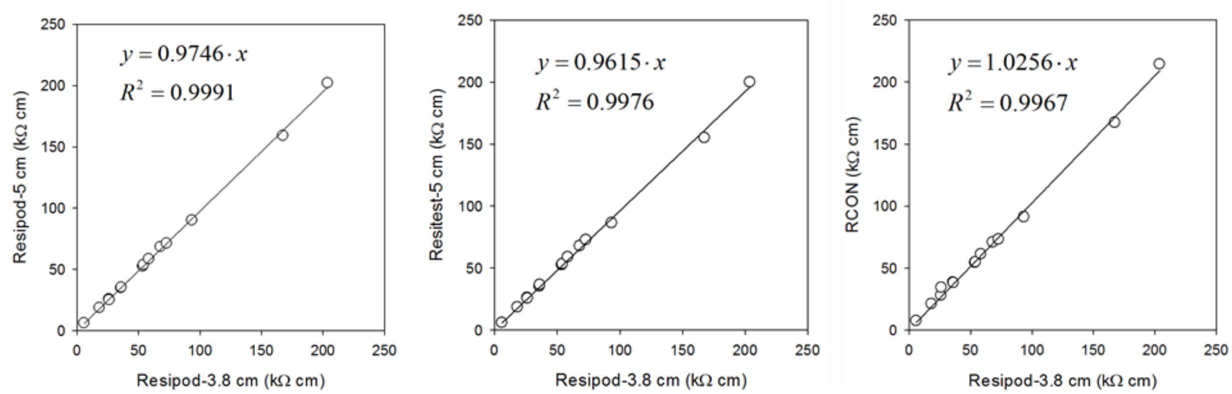


FIGURE 12 Comparison of bulk resistivity values measured with different resistivity meters.



(a) **(b)** **(c)**

FIGURE 13 Comparison between bulk resistivity values obtained from different meters with those obtained from Resipod meter with 3.8 cm spacing.

EVALUATION OF EIGHT VS. FOUR READINGS

The current FDOT and ASSHTO methods for surface resistivity measurement require eight resistivity readings by rotating the cylinder every 90 degrees. To reduce the work load, it is necessary to investigate if the resistivity measurement can be performed by taking four readings at 90 degree intervals without changing the precision of the measurement. FIGURE 14 shows comparison of average surface resistivity and coefficient of variation from eight and four readings. The data in FIGURE 14 is from measurements performed on around 500 cylinders from 14 mixtures at the age of 91 days in 14 laboratories. More details are included in a round robin test [12]. FIGURE 14 shows that the difference in the average resistivity and coefficient of variation from eight and four readings is almost negligible. Therefore, the surface resistivity measurements according to FM 5-578 or AASHTO TP 95 could possibly be performed by reducing eight reading to four readings (at 90 degrees interval) without reducing the accuracy or precision of the measurements.

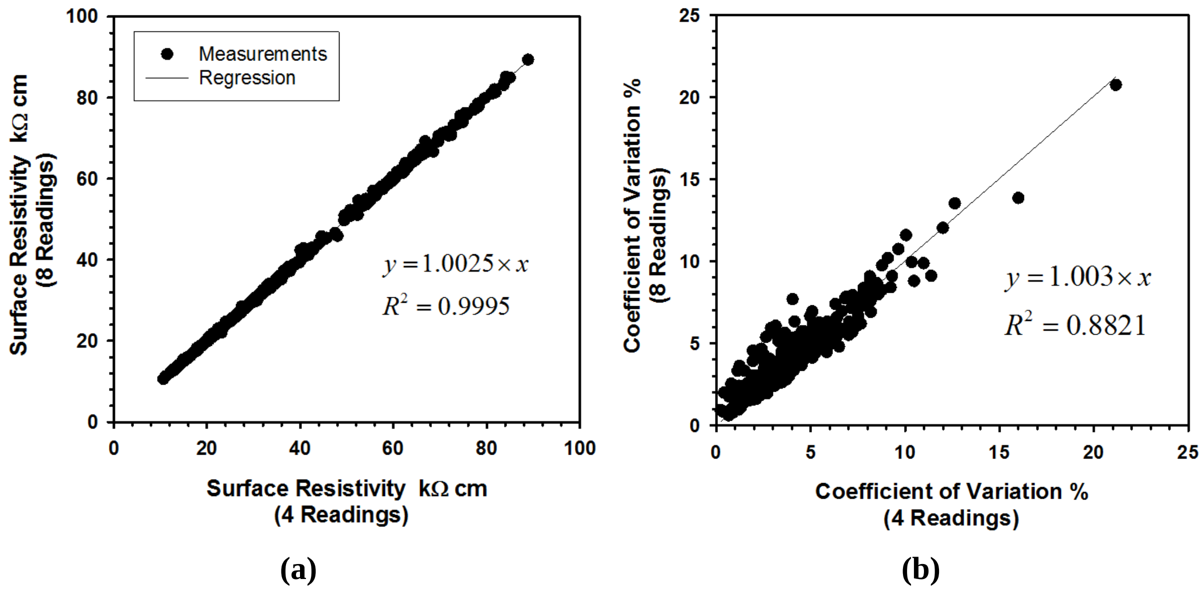


FIGURE 14: Comparison of surface resistivity with eight and four readings.

CONCLUSIONS

This paper introduces the methods for measuring the electrical resistivity of concrete and the corresponding factors which may affect the measured resistivity value. The following conclusions are dawn:

1. While comparing the resistivity values measured using different methods or resistivity meters, the factors which may affect the measured resistivity values should be taken into account, which include the geometry of specimens, the electrode spacing, degree of saturation, temperature, presence of rebar, etc.; and

2. When all these factors are taken into account and the measured resistivity values are converted to the bulk resistivity values at a reference temperature (e.g. 21°C), all the evaluated resistivity meters can provide consistent and reliable resistivity values;

3. The surface resistivity measurement using the Wenner method can be performed with four readings without reducing the accuracy or precision of the measurements.

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