Electrical Testing of Cement-Based Materials: Role of Testing Techniques, Sample Conditioning, and Accelerated Curing

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16. Abstract

These projects examined the potential for using electrical testing on concrete as a potential surrogate for obtaining information on ion and fluid transport. Electrical measurements are particularly attractive for use in quality control as they are easy to perform, are performed rapidly, and can be directly related to fluid transport. This work describes how electrical resistance measurements should be corrected for geometry to obtain a geometry independent resistivity or conductivity. Further, this work reviews and discusses several factors that influence the resistivity that is measured including porosity, pore connectivity, the role of temperature on degree of hydration (activation energy), temperature effects on conduction, ionic leaching, and the role of temperature and leaching on porosity. The goal of this work is to provide an overview of the main factors that should be considered when conducting electrical property testing, when using electrical properties for quality control/quality assurance, or if using these materials for acceptance. As a part of this project a series of testing devices were purchased and provided to the INDOT district testing labs for the purpose of providing training and providing information on the variability associated with testing. A round robin study has shown that a coefficient of variation of 4.36 % was obtained leading to a within laboratory precision of 12.8 % and a multi-laboratory precision of 36.0 %. This work has shown that temperature can dramatically influence the resistivity. The work has shown that in general for a standard 100 mm x 200 mm test cylinder, the ratio of surface resistivity to uniaxial resistivity, specifically the factor $\hat{k}2$ discussed in Section 5.1, is 1.9 for a homogenous material; however if the material is heterogeneous (due to drying or leaching) this value changes. This project has also illustrated the importance of ionic leaching. It was shown that accelerated curing requires temperature correction as well as control of ionic leaching. A direct correlation is discussed between electrical resistivity and the rapid chloride permeability test. At the current time, resistivity tests show promise in a quality control program, as a method of monitoring the variation associated with production. If used in this way, a trial batch could be used to develop target values, similar to that which is currently done with the maturity method. It is anticipated that an agency could eventually have the potential to use resistivity for mixture qualification; however, additional work is needed to correlate the resistivity with performance or service life models.

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EXECUTIVE SUMMARY

ELECTRICAL TESTING OF CEMENT-BASED MATERIALS: ROLE OF TESTING TECHNIQUES, SAMPLE CONDITIONING, AND ACCELERATED CURING

Introduction

To improve the durability of concrete pavements, concrete bridge decks, and other transportation elements there has been an emphasis placed on developing test methods to measure the durability of concrete mixtures. Tests for durability have been slow in implementation since they are time consuming to perform and often have high equipment costs. As such, these tests have are not ideal for use in a quality control setting. This project examined the potential for using electrical testing on concrete as a potential surrogate for obtaining information on ion and fluid transport.

The interest in rapid electrical measurements is high since it uses economic testing equipment whose measurements can be completed in a very short amount of time (on the order of one minute per sample). While several groups have used electrical testing over the last century to measure properties, this study has worked on details that are needed for the development of a more comprehensive standard testing protocol. The testing procedure is relatively straightforward. As a part of SPR-3657: Rapid Method of Mixture Acceptance, Indiana Department of Transportation (INDOT) district testing engineers and their technicians were trained. However, the data interpretation and sample conditioning process appears to make standard development a bit more challenging, especially when accelerated curing is used, as discussed in this report.

The electrical resistivity of concrete is related to the resistivity of the pore solution, the porosity of the concrete, and the tortuosity of the pore network. With the development of portable units that can be taken into the field, rapid measurements that can take less than one minute are gaining increasing interest as a quality control or mixture acceptance test method. This project has investigated the variability of these test methods as well as factors affecting measurements, including moisture and degree of saturation, temperature, geometry, leaching pore solution, and high temperature conditioning. This work describes how electrical resistance measurements should be corrected for geometry to obtain a geometry-independent resistivity. This work has shown that sample conditioning can influence the pore solution properties and degree of saturation considerably and that these factors need to be accounted for to obtain accurate measures of transport properties. This report outlines each of these effects.

Many research studies have evaluated the relationship between resistivity and the rapid chloride permeability test (RCPT). The experimental fits from the various research studies do not match the relationship from first principles, but a reasonable agreement is noted. One important observation is that while typically low values from RCPT are considered characteristic of high quality concrete, this corresponds to higher measurements from resistivity tests.

Major Findings

- This work has indicated that geometry correction factors are needed to convert resistance measurements into the geometry-independent value for resistivity or conductivity.

- This work has shown that for the uniaxial cylinder test a coefficient of variation of 4.4% was obtained, leading to a within-laboratory precision of 12.4% and a multi-laboratory precision of 37.38%.

- This work has shown that temperature can dramatically influence resistivity. A correction for measurements is needed when the sample is a temperature other than the reference temperature. This can substantially influence the results, and a correction factor has been proposed that is based on the pore solution composition.

- This work has shown that the degree of saturation can dramatically influence resistivity. A saturation function is proposed that accounts for drying as well as the concentration of pore solution.

- The work has confirmed that, in general, for a standard 100 $\times$ 200 mm test cylinder, the ratio of surface resistivity to uniaxial resistivity is 1.8 to 1.9 for a homogenous material; however, if the material is heterogeneous (due to drying or leaching), this value changes.

- This project has also illustrated the importance of ionic leaching. Specifically, when stored in lime, saturated water alkalis and hydroxide ions can leach from the pore solution into the surrounding pore solution. Additionally, the report discusses how ionic leaching would impact different concretes differently.

- It was shown that accelerated curing requires testing temperature correction and curing temperature correction. This leaching problem is also a temperature-related process, so specimens stored in lime water at different temperatures will show drastically different resistivity measurements, due in part to ionic leaching.

- A direct correlation is discussed between electrical resistivity and the rapid chloride permeability.

Implementation

The following suggestions are provided for implementation.

- Resistivity tests have the potential to be used as a mixture qualification tool. However, performance limits will need to be established for various INDOT applications. These can be based on historical performance or service life simulation.

- Resistivity tests can be used to replace RCPT testing, which could save INDOT money in terms of testing costs and could enable testing to be performed in district testing laboratories.

- It is recommended that resistivity testing be added to proficiency testing.

- It appears that INDOT should consider the specification of a formation factor for qualifying mixtures, which can be obtained from resistivity measurement normalized by the pore solution resistivity for a vacuum saturated sample. The pore solution can be determined using a calculation from the chemistry of the cement. Electrical measurements can be simultaneously performed using sealed specimens and this information can be used for quality control testing.

It is suggested that INDOT consider using the resistivity test as a quality control tool and mixture. Resistivity has been shown to be highly dependent on the paste content and water content in a concrete mixture, both of which are related to long-term durability. It is recommended that sealed resistivity measurements be conducted as a part of mixture qualification. Resistivity targets could be established to account for production variability and used to establish quality control limits. For this application, the use of a sealed specimen would be recommended.

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1. INTRODUCTION

There has been substantial recent emphasis placed on assessing the transport properties of the concrete used in transportation infrastructure. Several groups have sought test methods to assess the quality of concrete, however traditional transport test methods are difficult to implement due to their significant preparation, conditioning, and testing times.

This has led to a special interest in rapid electrical measurements. Rapid electrical tests utilize economical testing equipment and can be completed in a short amount of time, on the order of one minute per test. While electrical tests show great potential, there are several technical challenges that need to be addressed to ensure consistent results.

This study has worked toward the development of a standard testing protocol for measuring the resistivity of concrete, whose results would allow for the interpretation of the transport (diffusion) properties of a particular mixture. The testing procedure is straightforward, and as a part of SPR-3657: Rapid Method of Mixture Acceptance, INDOT district testing engineers and their technicians were trained and provided with the equipment and tools to conduct these tests. This included a training session co-hosted by the Joint Transportation Research Program and the Office of Materials Management in January 2013, and a software tool to assist with data analysis (1). A short video abstract was also completed to help provide context to resistivity testing of concrete and how this can serve to improve the quality of concrete used to make transportation infrastructure (2).

While electrical resistivity tests show great potential, there are several technical challenges that must be addressed to ensure consistent results. These challenges are related to sample conditioning and data interpretation, and are discussed in detail in this report and published research discussed as part of this research. Furthermore, while this report will highlight the industry adopted terminology of resistivity, typically given in units of ohms times meters ($\Omega \cdot$m) there exists significant research and data throughout the last century that has used the term conductivity, typically given in units of Siemens per meter (S/m). These parameters, resistivity and conductivity, are simply the inverse of each other.

2. BACKGROUND

2.1 Electrical Measurements in Porous Materials

Electrical measurements in porous materials (like concrete) can be described using Equation 1:

$$\rho_T = \rho_o \cdot \frac{1}{\phi \beta} \qquad (1)$$

where ρ_T is the total resistivity, ρ_o is the resistivity of the pore solution which is a function of the ions composition and concentration in solution, ϕ is the porosity of the system that is accessible to fluids, and β is the connectivity of the pores in the system (3). A schematic of these different factors is shown in Figure 2.1. As discussed subsequently, the term $1/\phi\beta$ is sometimes grouped into a single parameter, F, the formation factor (4).

One of the major assumptions of this law is that the solid skeleton is non-conductive, which is true for many types of rocks and cement materials (3). This assumption would be violated in materials containing steel reinforcement, steel fibers, or samples where lightweight aggregates are saturated with a low resistivity solution (6,7). In these cases, results should be interpreted carefully.

2.2 Pore Solution in Cementitious Systems

The electrical conduction in cementitious materials occurs primarily through the fluid phase, i.e., the pore solution, as shown previously in Equation 1 and Figure 2.1a.

While this solution will start as the water used in the mixing process, as the water and cement react, the cement will release conductive ions into the pore solution. These ions are positively or negatively charged and are primarily: Potassium (K^+), Sodium (Na^+), Calcium (Ca^{2+}), Hydroxide (OH^-), and Sulfate (SO_4^{2-}). However, the exact composition and concentration will depend on the chemistry of the cementitious materials, the amount of water initially added to the mixture, and the extent of the reacted materials, i.e., the degree of hydration of the cementitious materials.

Experimental techniques have been developed to determine the resistivity of the pore solution, (8), but this is time consuming to perform and is difficult at

ρ_o ϕ β

(a)   (b)   (c)
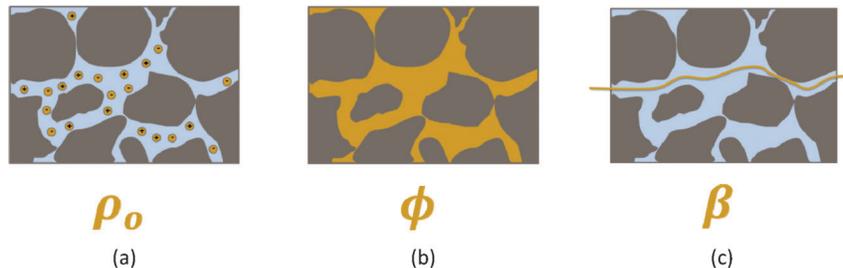
Figure 2.1 Schematic highlighting the parameters used to describe electrical measurements in porous materials for (a) resistivity of the pore solution (b) porosity and (c) connectivity, reproduced from (5).

Figure 2.2 Screenshot of the pore solution conductivity calculator (*11*), available at http://concrete.nist.gov/poresolncalc.html.

later ages due to the small volume of pore fluid available for analysis. Work in the late 1980's by Taylor developed a method to determine the concentration of ionic species in the pore solution based upon the chemistry, specifically the alkali content, of the cementitious materials (*9*). In 2002, Snyder et al. of the National Institute of Standards and Technology (NIST) developed a technique to determine the resistivity of the pore solution using the concentration of different ionic species (*10*).

This approach was programmed into a web application by Bentz (*11*), which can be found at concrete. nist.gov/poresolutioncalc.html. A screenshot is shown in Figure 2.2. This website is especially powerful in that it allows the user to enter data from the cement's mill certificate and the anticipated mixture design to

estimate the pore solution composition and conductivity for different concrete mixtures.

2.3 Microstructural Factors: The Formation Factor

The resistivity of a saturated porous material depends strongly on two microstructural parameters: the porosity, ϕ, and connectivity, β, of the system. As illustrated in Figure 2.1, the porosity is a term that describes the volume of pores in the system and the connectivity characterizes how these pores are connected through the three-dimensional system.

It is often difficult to separate these two terms, so literature often presents the product of these two terms together, whose inverse has been termed the Formation Factor. This relationship is shown in Equation 2:

$$\phi\beta = \frac{1}{F} \qquad (2)$$

where ϕ is the porosity, β is the connectivity, and F is the Formation Factor.

These parameters are *material properties*, which are independent of specimen size or shape, but are dependent on mixture characteristics such as the water-to-cementitious materials ratio, volume of paste, and degree of hydration (*12–14*). They can change as the system hydrates and ages, often by several orders of magnitude in typical cementitious systems (*15*).

2.4 Nernst-Einstein Relationship

The porosity and connectivity, or the Formation Factor, are typically referred to as transport properties because they can be used to describe the diffusion of ionic species in porous materials. Diffusion is the process by which ions move through the pore solution due to differences in concentration, and is often considered the main transport mechanism for chloride ions in (saturated) cement-based materials.

The formation factor is related to the diffusion coefficient by what is known as the Nernst-Einstein Relationship (*4*). This is presented in Equation 3:

$$\frac{\rho_T}{\rho_o} = F = \frac{D_o}{D} \qquad (3)$$

where ρ_T is the total resistivity, ρ_o is the resistivity of the pore solution, F is the Formation Factor, D_o is the self-diffusion coefficient which describes how different ionic species move through dilute solutions, and D is the bulk diffusion coefficient. The self-diffusion coefficient, D_o, can be determined for different ionic species (usually for a cation-anion pair), e.g., (*16*). For a chloride ion at 23 °C, a typical value for D_o is 1.9×10^{-9} m^2/s (*17*).

2.5 Additional Considerations

This section has discussed electrical measurements on porous materials that have been developed over the past century. Much of this knowledge has come from testing of rocks and ceramics, intentionally saturated with solutions of known resistivity (*4,18*). Resistivity tests of concrete have one glaring difference: the microstructure and pore solution in concrete are changing significantly over the concrete's lifetime, while those of rocks and ceramics are relatively constant.

In fact, the environmental conditions (or curing conditions) can significantly impact these changes in microstructure and pore solution. Past research has shown that sealed curing versus water curing can lead to a significantly different extent of reaction (degree of hydration), which will affect both the microstructure and the pore solution properties (*19,20*). Field structures are often thought of as being somewhere in between these two idealized curing conditions. Presuel-Moreno et al. have shown that storage in lime water versus storage in a 100% relative humidity chamber can lead to differences in electrical measurements (*21*). Spragg et al. have shown a significant dependence on the volume of solution surrounding the test specimen, which is likely related to the leaching of conductive alkali species from the pore solution into the surrounding storage solution (*20*). It has also been demonstrated by Bu et al. that this leaching of alkalis can influence the microstructure (*22*). Additionally, Weiss et al. showed a significance depending on the moisture content, although a simple correction can be applied (*19*). It should be noted that these factors will affect different concretes differently, as the alkali content of the cement, water-to-cementitious materials ratio and porosity, paste volume, and degree of hydration (age) will factor into the impact of these effects.

Historically, these factors have been combined into a single correction factor or a correction factor for hydration and conduction (*23,24*). However, this study has proposed a general equation to account for all of these factors on measurements of electrical resistivity at an equivalent age in cementitious systems in Equation 4:

$$\rho_{T_{ref}} = \rho_o^* \cdot F \cdot f(S) \cdot f(T_{test}) \cdot f(Leach) \cdot f(Microstructure) \qquad (4)$$

where $\rho_{T_{ref}}$ is the resistivity at a reference temperature at an equivalent age of t_{eq}, ρ_o^* is the resistivity of the pore solution at saturation, F is the Formation Factor, $f(S)$ is a saturation function, $f(T_{test})$ describes the effect of testing temperature on resistivity measurements, $f(Leach)$ is a leaching function, and $f(Microstructure)$ is a microstructure function. The equivalent age t_{eq} is a function of the time and temperature history, i.e., maturity or degree of hydration, and is discussed in Section 7.5.

The factors will be discussed in detail in Chapter 7, and serve to highlight the complexity of understanding the impact of curing on electrical measurements. The authors believe that for determining and properly comparing transport properties, these effects should be considered in standard test methods (*5*).

3. HISTORY OF ELECTRICAL MEASUREMENTS IN CEMENTITIOUS SYSTEMS

Electrical measurements of cementitious materials have been studied for nearly a century. In the 1920's, electrical measurements were used to determine time of set (25). Since the 1950's, many studies have focused on the use of electrical measurements as a method of characterizing the microstructure of cement-based materials. In 1955, Hammond and Robson showed resistivity measurements for a series of different cements, ranging from portland cement to high alumina cement (26). In the 1960's, the U.S. Navy was developing resistivity tests for concrete (27). The Portland Cement Association highlighted the age dependency and heterogeneous nature of cement paste, and showed that mortar resistivity could be predicted based upon measurements done from the paste (28). McCarter et al. studied the influence of mixture proportions, electrode configuration, and temperature (13,29,30). Gu et al. and Xie et al. developed equivalent circuit models that have led to our understanding of the electrical response across a wide-range of frequencies (14,31). Schiessel et al. showed that the frequency that should be used reduces over time, and changes in the response across multiple frequencies can be related to changes in the microstructure and moisture content (32). Christensen et al. were able to relate electrical properties to decreasing porosity as the cementitious materials hydrates, and were also able to highlight that using simple assumptions, an estimation of the diffusivity of ionic species, e.g., chloride ions, can be determined within reasonable accuracy (12).

In the 1980's, Whiting worked with the Strategic Highway Research Program (SHRP) to develop a test method that has since become known as the Rapid Chloride Permeability Test (RCPT) (33). Although it is a test that depends upon a specimen's electrical properties, it measures the total charge passed over a six hour period when a constant voltage is applied. The resistivity and total charge passed can be directly related, and is discussed further in Chapter 8. However, this test, while widely used, has numerous shortcomings which have been discussed in the literature, e.g., Spragg et al. (34). Most notable, are spurious results due to temperature (specimen heating) effects and microstructural changes due to the high voltages (35,36).

With the development of portable units that can be taken into the field, rapid resistivity measurements that can take less than one minute are gaining increasing interest. These measurements were first started by Millard (37). A recent study by Rupnow et al. has highlighted the significant cost savings of these rapid tests due to economical equipment, approximately 3,000 USD, and comparatively short sample preparation time (38). Previous work in the literature has focused on the variability of these test methods (34,39), factors affecting measurements, including: moisture and degree of saturation, temperature, geometry, pore solution, and conditioning (19,20,23,24,38,40–42).

This report has highlighted the use of these tests methods in the State of Indiana and the development of a standard test methodology for their use. While the testing procedure has been firmly established, an unexpected significant dependency on sample conditioning has been found.

4. TESTING PROCEDURES

There currently exist three types of test methodologies for resistivity measurements of concrete. The first two, surface and uniaxial, are currently being considered for potential standardization through the American Association of State Highway and Transportation Officials and ASTM International. These tests have been used extensively in the literature and will be discussed further in this section.

Resistivity tests are a nondestructive test that can be performed on a wide-range of testing geometries. The most popular has been the use of standard 100 mm × 200 mm test cylinders. Figure 4.1 shows the use of (a) surface resistivity and (b) uniaxial resistivity tests on standard test cylinders.

Another configuration utilizes embedded sensors. These have been used extensively in the literature, e.g., (15,32,41,43–46). These are often sensors that can be placed directly into the fresh concrete and cast-in-place. Examples of these geometries are shown in Figure 4.2. These have the benefit of being able to be placed into a specimen that is then sealed and testing would not necessitate removal from a sealed condition and risk extensive loss of moisture. This would be ideal for the monitoring of sealed specimens.

5. GEOMETRY EFFECTS

As discussed previously, *resistivity* is material property that is independent of specimen geometry and electrode configuration. However, the *resistivity* is determined from a test of *resistance*. This resistance must be corrected for specimen size and electrode configuration to determine the resistivity. This correction has traditionally been termed the geometry factor, denoted using k, and shown in Equation 5:

$$\rho = R \cdot k \qquad (5)$$

where ρ is the resistivity, R is the measured resistance, and k is the geometry factor. These factors can be determined experimentally by comparing to measurement of a solution of known resistivity or numerically (15,20,47). The units of resistivity are typically ohm × length, where the ohm comes from the measure of resistance and the measure of length comes from the geometry factor.

If this correction is not done, resistance measurements can vary by orders of magnitude, as shown in Figure 5.1a. When the resistance is multiplied by the correct geometry factor, the different resistivity tests will show consistent results, as illustrated in

(a)

(b)

Figure 4.1 Common testing geometries used on standard 100 mm × 200 mm test cylinders in the (a) surface and the (b) uniaxial configurations, reproduced from (*5*).

(a)
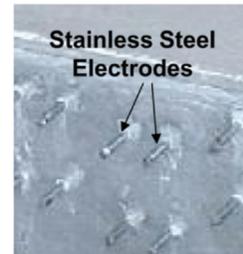
(b)

Figure 4.2 Examples of embedded sensors that have been reported in literature by (a) Castro et al. (*43*) and by (b) Weiss (*41*).

Figure 5.1b, using different pieces of equipment (noted in the legend by the name of the manufacturer) and test geometries.

Figure 5.1 also highlights the importance of checking the test equipment against an unchanging reference at every use. Low batteries can produce errors in the measurements even before low battery indicators give a warning. An unchanging reference can simply be a circuit board with values of known resistance.

It should be noted that geometry factors are often developed using the assumption that the material being tested is homogenous. However, as discussed in Section 7.3, this is not always the case in cementitious systems. In cases where the system is not homogenous, the geometry factor can differ significantly, and will require additional analysis for proper comparison.

5.1 Surface Configuration: Wenner Test

The surface resistivity test, often termed the Wenner test, was initially developed for use in soil testing by Frank Wenner at the National Bureau of Standards in the 1910's (*48*). A schematic of the four-point surface resistivity test applied to a concrete cylinder is shown in Figure 5.2.

In the development of the test method, an assumption of an infinite half-space was assumed, i.e., the spacing of the electrodes is much smaller than the depth of the material being measured ($a \ll d, L$). If this criteria is satisfied, the geometry factor is given by $\hat{k}_1$ in Equation 6:

$$\hat{k}_1 = 2\pi a \qquad (6)$$
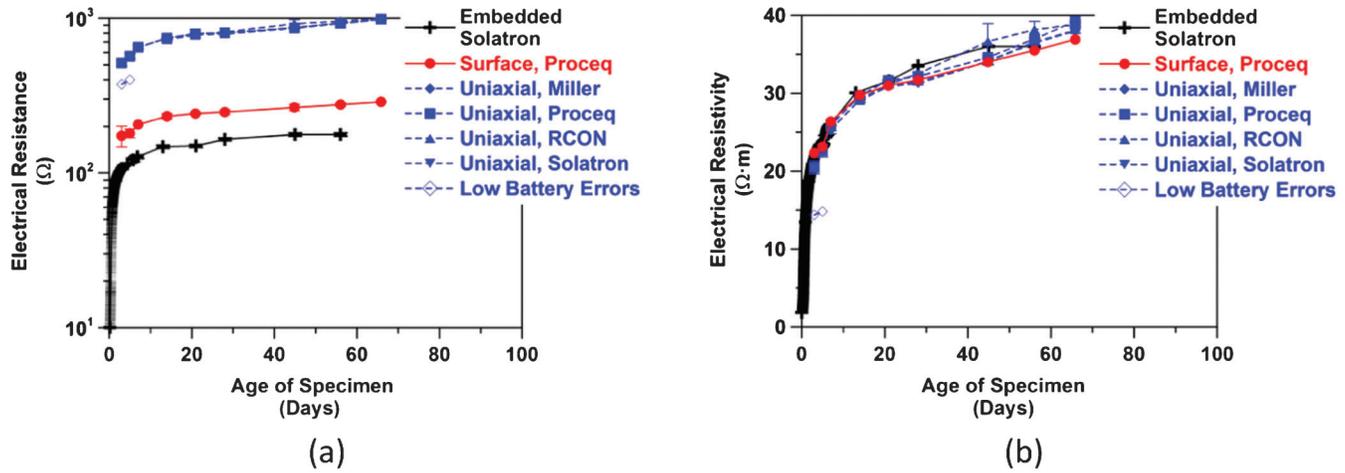
Figure 5.1 Electrical measurements, described in (*20*), conducted on sealed replicate specimens showing (a) resistance measurements (made without geometric correction) that differ by orders of magnitude and (b) the resistivity corrected for geometry. Error bars represent the standard deviation of three specimens.

where *a* represents the spacing of the electrodes. Many commercial surface resistivity meters do this correction automatically.

However, when testing is conducted on a cylindrical concrete test specimen, the assumption of infinite-half space is not valid because of the small testing geometry and the large probe tip spacing that is required to prevent interferences with coarse aggregates (*47,49,50*). An additional factor is often needed to account for constricted flow in the material. Morris et al. (*47*) has shown, using finite element simulation, the magnitude of additional corrections needed when using surface resistivity tests on various cylindrical geometries. Spragg et al. (*20*) has fitted this data to present the factor termed $\hat{k}_2$ in Equation 7:

$$\hat{k}_2 = 1.10 - \frac{0.730}{d/a} + \frac{7.34}{\left(d/a\right)^2} \quad (7)$$

Figure 5.2 Schematic of the surface resistivity test being conducted on a test cylinder, reproduced from (*5*).

where *a* represents the spacing of the electrodes, *d* is the diameter of the test cylinder. It should be noted that this correction is only when $d/a \leq 6.0$ and $L/a \geq 6.0$, where *L* is the length of the cylinder. For testing on a standard 100 mm × 200 mm test cylinder, this value ranges from 1.8 to 1.9.

Often times, $\hat{k}_1$ is applied automatically by the resistivity meter before a number is displayed on the machine. In that case, $k = 1/\hat{k}_2$ should be applied. In the case that the resistivity meter simply shows the measured resistance, the geometry factor for a surface test is given by Equation 8:

$$k = \frac{\hat{k}_1}{\hat{k}_2} \quad (8)$$

It also worth noting that Equation 7 is only valid for a (spatially) homogeneous system, and shows good agreement when the material is indeed homogeneous. When the sample has heterogeneity, due to drying or chemical changes, additional corrections are needed. These will be discussed further in Chapter 7.

The surface resistivity test has gained popular usage by the Florida (*51,52*) and Louisiana (*38,53*) Departments of Transportation. Many sources in the literature advocate the use of this method because it can allow for measurements in-situ, but a dependence on geometry, degree of saturation, leaching of alkalis and ingress of deicing salts applied from deicing operations, temperature, and location of reinforcing steel, means that in-situ measurements should be interpreted carefully.

5.2 Uniaxial Configuration

The uniaxial resistivity test is another resistivity configuration for use on a concrete specimen (*13*). A schematic of the uniaxial test is shown in Figure 5.3. This configuration typically consists of a set of plates
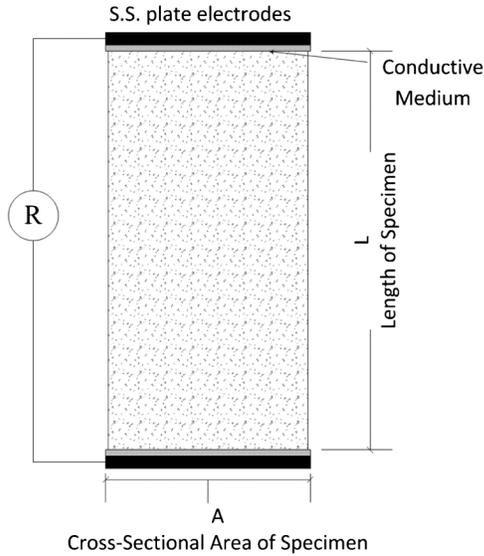
Figure 5.3 Schematic of the uniaxial resistivity test being conducted on a test cylinder, reproduced from (5).

that are placed at the ends of the specimen with a conductive medium, typically a wet sponge or conductive gel, being used to create good electrical contact between the specimen and the electrodes.

This configuration has the benefit of a more uniform current distribution throughout the sample, and is not as dependent on surface characteristics. The geometry factor for this configuration is shown in Equation 9:

$$k = \frac{A}{L} \qquad (9)$$

where A is the cross-sectional area of the specimen and L is the length of the specimen, or the distance between the plates.

One of the important assumptions of this test is that there is a good electrical connection between the test specimen and the electrodes, typically accomplished through the use of a conductive medium (54). This can be a conductive gel, a wet paper towel, or a saturated sponge (34,55,56). In some cases, these elements have an associated resistance. There has been a correction proposed to the measured resistance, to correct for the resistance of the sponges, shown in Equation 10 (for resistors in series) (54):

$$R = R_{measured} - R_{top\ sponge} - R_{bottom\ sponge} \qquad (10)$$

where R is the resistance used in Equation 5, $R_{measured}$ is the measured resistance of the top sponge, specimen, and bottom sponge, and $R_{top\ sponge}$ and $R_{bottom\ sponge}$ are the resistance of just the top and bottom sponge, respectively. When measuring the resistance of each sponge, it is important to use the pressure that each sponge sees during the resistivity test. An example is shown in Figure 5.4.
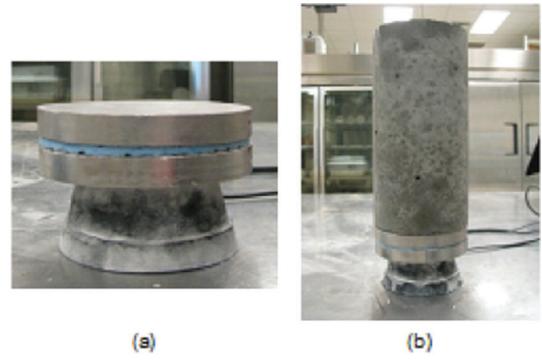
Figure 5.4 Configuration for the measurement of (a) $R_{top\ sponge}$ and (b) $R_{bottom\ sponge}$, reproduced from (5).

5.3 Embedded Configuration

The last configuration is the embedded configuration. While the literature has had many successful variants of the embedded sensor, one that has shown particular promise is a set of stainless steel rods in a standard 150 mm × 300 mm test cylinder, shown here in Figure 5.5.

This particular configuration has been described elsewhere in the literature, e.g., (20,43).

For this configuration, the geometry factor often needs to be determined numerically or experimentally. The experimental determination can be done using a
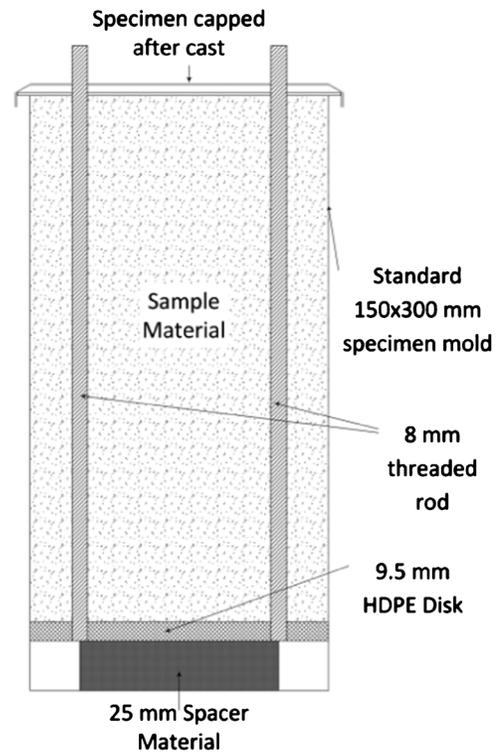
Figure 5.5 Schematic of the embedded configuration in a modified 150 mm × 300 mm test cylinder, reproduced from (5). (HDPE = high density polyethylene).

solution of known conductivity, such as potassium chloride whose conductivity is presented in many chemistry or physics handbooks, e.g., (16). It is worth noting that a solution of significantly low resistivity, i.e., higher concentration, should be used, as high resistivity solutions can introduce spurious results.

6. VARIABILITY

The variability associated with test methods on cement-based materials arises from many factors. In general, the total variation can be explained by Equation 11, as discussed in (57):

$$\sigma_{total} = \sqrt{\sigma_{machine}^2 + \sigma_{operator}^2 + \sigma_{material}^2 + \sigma_{production}^2 + \sigma_{curing}^2}$$

(11)

where the subscripts denote variation from the testing machine, test operator, material variability, production, and curing conditions between laboratories, respectively. Using a series of measurements from the laboratory, values for machine, operator, and material variability were calculated as 1.7%, 1.8%, and 3.4%, respectively. This matches studies by Poursaee et al. (45), Rupnow et al. (38), and Spragg et al. (34) which have shown the combined variation of machine, operator, and material has a coefficient of variation of approximately 3% to 4%. This variability is typically thought of as the repeatability of the measurements.

The variation due to production is also included in total variation. This could be assessed by variation of the electrical measurement assessed on different batches with the same nominal design over a period of time. Data discussed by Spragg from an Indiana paving contractor, during the summer of 2012, measured electrical resistivity before testing beams for flexural strength (5). The total coefficient of variation that was measured was 11.0%. If Equation 11 is used to calculate the production variability, using values of machine, operator and material variability discussed previously, a production variation of 10.2% can be determined. For a frame of reference, during the same time period, this contractor had a variation in water-to-cementitious materials ratio of 3.5% and a variation in measured flexural strength of 5.9%.

6.1 AASHTO Round Robin

A fourteen laboratory round robin evaluation for the development of precision statements was conducted in 2011 (34,39). The data was used to calculate the within-laboratory and multi-laboratory coefficient of variation which allowed for the development of the precision statement, according to ASTM C670-10 (58).

The within-laboratory and multi-laboratory precision indices for the surface and uniaxial test are shown in Table 6.1, as determined by Spragg et al. (34). It is worth noting that these values are slightly higher than the report that was prepared detailed from that part of the study, but were prepared to remain consistent with

TABLE 6.1
Precision indices for the surface and uniaxial resistivity test, described in (34)

Testing Method	Within-laboratory	Multi-laboratory
Uniaxial resistivity	12%	37%
Surface resistivity	13%	35%

the uniaxial indices and under the advisement of the Purdue Statistical Consulting Service.

The precision indices can be interpreted as the difference between the average of measurements from each test method. For example, the within-laboratory precision for uniaxial resistivity of 12% means that for any two properly conducted tests in the same laboratory, the difference between them should not be more than 12% of their composite average. With a multi-laboratory index of 37%, the difference between any two properly conducted tests in different laboratories should not be more than 37% of their composite average. This can be compared to an RCPT test, which has a multi-laboratory precision index of 51% (59).

It is also worth noting that specimens in this round robin were distributed at an age of 14 d, then cured further and tested in the participating laboratories, up to ages of 91 d. Moreover, the curing condition was potentially not as one may have expected, i.e., temperature was allowed to vary, laboratories were allowed to use 100% RH curing rooms or tanks of lime water, some laboratories used curing tanks and others used buckets. All of these factors have been shown to influence resistivity measurements (20).

The coefficients of variation reported in this study were a within-laboratory index of 4.36% (which includes variation due to machine, operator, and material) and a multi-laboratory index of 13.22%. As all of the 14 mixtures were made from a single batch of that mixture, there was no production variation. Using Equation 11, the variation due to different curing methodologies (i.e., lime water curing, moist curing room, variations in temperature) is 12.48%. This suggests that if the curing condition was fixed between laboratories, a much lower variation between laboratories would be expected.

6.2 INDOT District Laboratories

As part of SPR-3657, Purdue supplied two Class C concrete mixtures to INDOT district testing engineers and their technicians. Both of these mixtures were made at the Pankow Materials Laboratory at Purdue University, using local ready-mix suppliers.

The first of the concrete mixtures was distributed at an age of 90 d. Subsequent resistivity measurements were performed by district laboratories, using both the uniaxial and surface configurations, at ages indicated on the x-axes of Figure 6.1. The figures are overlaid with the precision indices for within laboratory
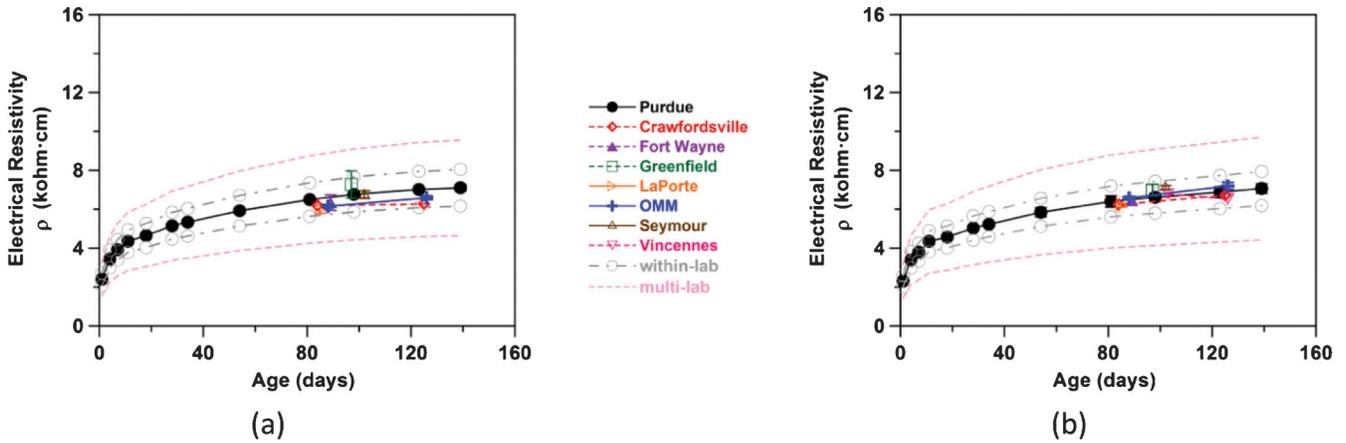
Figure 6.1 Variability between measurements on a Class C concrete distributed at a late age (greater than 90d), in (a) surface and (b) uniaxial configuration. Error bars represent a standard deviation for 3 specimens and figures are overlaid with precision indices discussed in Section 6.1, reproduced from (*5*).
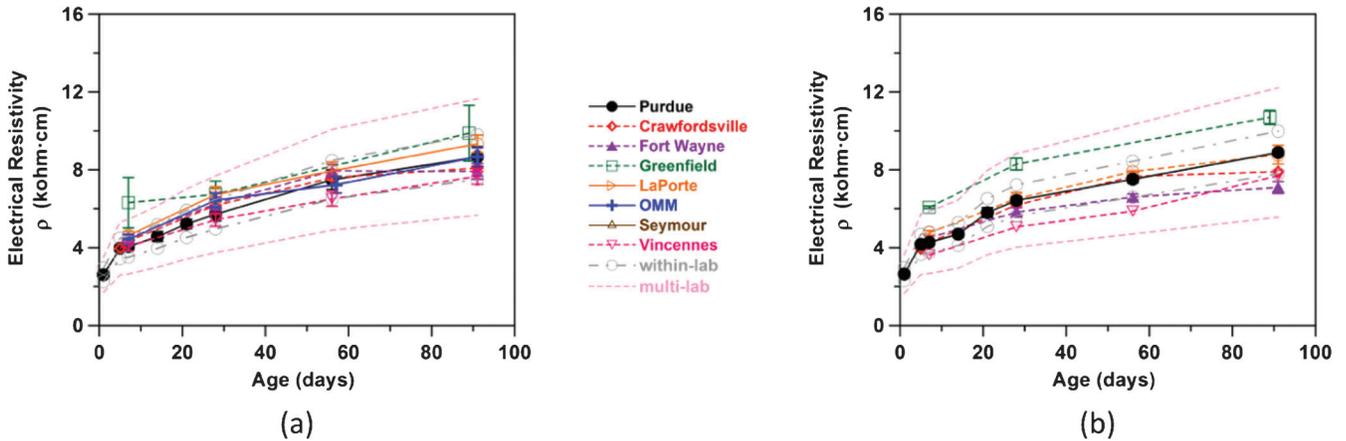
Figure 6.2 Variability between measurements on a Class C concrete distributed at an early age (less than 7d), in (a) surface and (b) uniaxial configuration. Error bars represent a standard deviation of 3 specimens and figures are overlaid with precision indices discussed in Section 6.1, reproduced from (*5*).

(shown using hollow circles) and multi-laboratory variation (shown with dashed lines). It can be seen that when multiple labs test specimens distributed at a late age, the variation is well below that allowed for multi-laboratory, and in many cases is lower than within-lab variation. This suggests that variation due to curing, as discussed above, is significant and should be controlled.

The second concrete mixture was distributed less than 7 d after casting to the district testing offices, with districts subsequently reporting resistivity measurements at ages indicated on the x-axes of Figure 6.2. It is noted that higher variation is seen in the specimens distributed at an earlier age Figure 6.2.

7. ADDITIONAL FACTORS

7.1 Degree of Saturation

The impact of the degree of saturation on resistivity measurements of porous materials has been studied by

a series of researchers (*28,32,42,44,60*). Weiss et al. proposed a correction, or a saturation function, that would allow for the resistivity at any level of saturation to be corrected to a comparative measurement at a saturated state (*19*). This is a power law correction, shown here in Equation 12:

$$f(S) = S^m \tag{12}$$

where S is the degree of saturation (ranging from 0 at a completely dry state to 1 at full saturation) and m is a fitting coefficient that has been shown to range from 3.0 to 5.0 (*19*). This fitting parameter has been shown to relate to the connectivity of the fluid phase and pore solution and its ionic strength during drying, and more information is available in the literature (*19*). This exponent can also be determined experimentally, by saturating a specimen and taking electrical and mass measurements as it dries.

It is also worth noting that curing in a lime water bath or in a humidity room does not guarantee that a concrete remains in a saturated condition. This should

be evaluated in the cases of high-performance concretes where the capillary porosity becomes disconnected (61).

Furthermore, measurements on air-entrained concretes should be interpreted carefully. It is often thought the air-entrained pores are not filled with water, even when stored under water (62). A recent technical note by Bu et al. evaluated an air-entrained concrete with a fresh air-content of 6.2% and total porosity of 18.5%, with respect to saturation (63). If the assumption is made that even half of the air entrained voids are empty, the degree of saturation can be calculated as 0.83. Using this saturation function correction, it is possible that resistivity measurements would be up to twice as high as in a completely saturated system.

7.2 Testing Temperature

Temperature can significantly influence the measured resistivity, with higher temperatures leading to lower resistivity values, as demonstrated in Figure 7.1.

Early work focused on a linear correction at different temperatures, (13), but more recently literature has used an activation-energy-based exponential relationship presented in Equation 13 (64).

$$\frac{\rho_{T_{ref}}}{\rho} = \exp\left[\frac{\mathrm{E}_{a-cond}}{R}\left(\frac{1}{T} - \frac{1}{T_{ref}}\right)\right] \qquad (13)$$

where $\rho_{T_{ref}}$ is the resistivity at the absolute reference temperature T_{ref}, usually 23 °C in the United States, ρ is the resistivity at absolute temperature T, E_{a-cond} is the parameter described as the activation energy of conduction, and R is the universal gas constant [8.314 J/(mol·K)]. Values of this ratio for ranges of E_{a-cond} that are reported in the literature are shown in Figure 7.2. It should be noted that this equation differs from the equation that describes the influence of temperature on hydration rate, see Section 7.5, by a

negative sign that will appear in front of the activation energy (since higher temperatures produce faster hydration but lower values of resistivity).

It should be noted that a lower activation energy of conduction corresponds to a measure that is less temperature-dependent. Experimental measurements conducted by the authors on solutions with high ionic concentration exhibit a lower activation energy of conduction.

A few observations should be noted regarding temperature corrections. First, the activation energy of conduction is not related to the activation energy of hydration, as these two parameters describe two distinctly different temperature phenomena. The activation energy of hydration, discussed in Section 7.5, describes the influence of temperature on the hydration rate of cementitious materials. The activation energy of conduction describes the influence of temperature on resistivity measurements, since the pore solution becomes more conductive at higher temperatures. Secondly, literature has reported that in the narrow temperature range of 22.7 °C to 24.4 °C (the range specified by the standard test method), temperature is not an important factor in resistivity measurements (53). However, larger temperature variations are typically seen in practice. The use of an exponential approach using an activation energy of 23 kJ/mol in this temperature range is consistent with that finding, as the temperature factor for this range varies from 0.99 to 1.04, which is within the variability seen by a single operator (34,39). However, beyond this range from 10 °C to 40 °C, both of which could be temperature ranges experienced on a jobsite or in an uncontrolled laboratory, the resistivity can vary from half to one and half times the expected value at a reference temperature, as shown in the vertical axis in Figure 7.2.
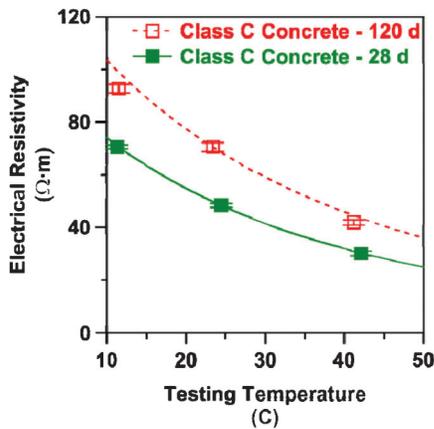
Figure 7.1 Influence of specimen temperature on measured resistivity. Dashed lines indicate a correction using an activation energy of conduction of 22 kJ/mol, error bars represent a standard deviation of 3 samples, reproduced from (5).
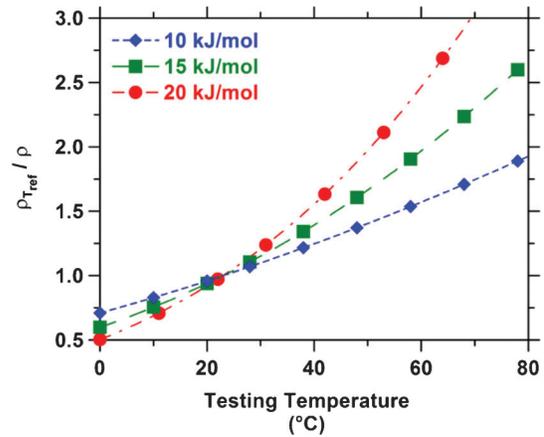
Figure 7.2 Ratio of resistivity at a reference temperature of 23 °C to the measured resistivity at a different testing temperature for a series of different activation energies of conduction, E_{a-cond}, and specimen temperatures, reproduced from (5).

7.3 Leaching of Alkalis from Pore Solution

For quite some time, the dissolution of the reaction product calcium hydroxide (CH in cement chemistry notation) in plain water has been recognized, which is primarily driven by the difference in concentration between the concrete and the storage solution. This concentration difference can cause leaching of CH, increase in porosity and reduction in strength (65). For this reason, curing in lime-saturated water has been suggested for many years, e.g., (66).

However, electrical measurements also depend most strongly on the sodium, potassium, and hydroxide ions in the pore solution, as discussed in Section 2.2. Storage in lime saturated water, which is currently done and suggested by the draft standards, can cause differences in concentration in the alkalis in the pore solution and storage solution. This can lead to the diffusion of alkalis out of the test specimen and into the storage solution to attempt to equalize the concentration. This effect has been noted in the field of Alkali-Silica Reaction research (67–69), and work is currently underway to more rigorously describe the impact on electrical measurements. Initial measurements suggest that the pore solution resistivity can vary by 80% depending on curing condition (70).

Alkali leaching phenomenon presents a few challenges as it relates to electrical measurements. First, leaching of alkalis can lead to the formation of a gradient of pore solution resistivity. Namely, the outer surface of the test cylinder will lose alkalis which will increase the resistivity of the pore solution while the inner core will remain at high concentration. This leads to the development of a material in-homogeneity, which will influence the measurements and the relationship between test geometries (5). Secondly, the leaching is a time dependent process that is influenced by the diffusivity of the material, curing temperature, and the alkali content of the pore solution. Because of this, it is difficult to describe the influence and impact on every type of concrete.

One possible methodology of reducing this leaching problem is to store the samples in an artificial pore solution that closely matched the pore solution of the concrete mixture (5). Initial results from this study, shown here in Figure 7.3, show that the lime water curing shows resistivity values that are 30% to 40% higher than storage in pore solution, which is consistent with leaching.

However, this technique does have some concerns. First, specimens cured in pore solution tend to show higher variation, as seen by the standard deviation error bars in Figure 7.3. This may be due to the formation of surface deposits that should be scraped away before testing. Bu et al. are also currently working to show that the alkali content of a mixture can influence the quality of hydration products (22). Furthermore, there are significant safety concerns for practitioners, as an artificial pore solution has a high alkali content and requires personal protective equipment (PPE) when using.
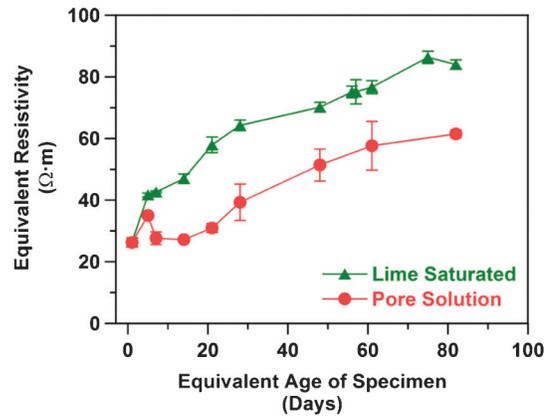
Figure 7.3 Electrical measurements conducted on a Class C concrete stored in lime saturated water (standard curing) and in artificial pore solution using a solution to sample volume ratio of 2.0. Error bars represent the standard deviation of three specimens, reproduced from (5).

A study by Spragg et al. (70) that is currently in progress will present a possible correction for the pore solution that is based upon this leaching phenomena. However, the suggested methodology is the use of sealed specimens that can be corrected to saturated conditions using the saturation function (5).

7.4 Microstructure Function

Curing temperature has direct effects on the microstructure of the concrete materials and as such would also influence the electrical measurements (71). Results have shown that accelerated curing at 45°C results in, on average, an 11.1% increase in porosity, a 17.5% increase in chloride diffusion coefficients and a 71.2% increase in moisture permeability in concrete specimens, compared to standard curing at 23°C. While temperature seems to be the apparent reason causing such microstructural differences, roots of these changes are suspected to be (1) the effect of temperature on the morphology of C-S-H (72,73), (2) the leaching of hydration products (74) and (3) the leaching from pore solutions of alkali ions, the concentration of which has been shown to have direct influence on the microstructure of cementitious materials (22). Further research is being done to evaluate the weighing of each of the three stated factors on the overall microstructural changed observed. Therefore, care needs to be taken when accelerated curing at higher temperature is combined with electrical measurements as quality control methods.

7.5 Aging Function: Activation Energy of Hydration

The influence of temperature on the rate of chemical reactions has been studied since the 1890's, and for the last half-century the effects on temperature on portland cement systems has been studied (75,76). Early efforts evaluated a simple product of time and temperature, termed the Nurse-Saul Maturity Index, which assumed

a linear relationship between the rate of reaction and temperature. Freisleben-Hansen and Pedersen were able to bring the scientific study of chemical reaction kinetics to use in civil engineering and proposed the use of an exponential relationship (77), whose primary input is the activation energy.
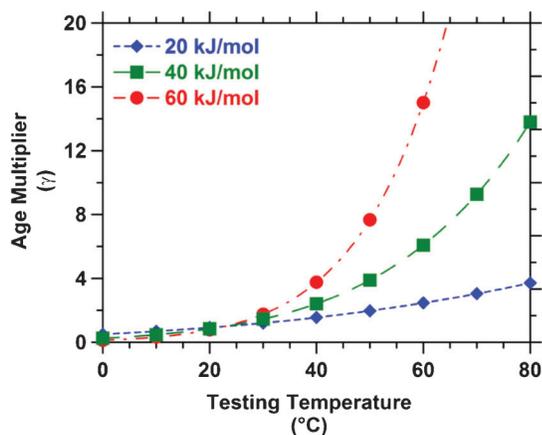
The activation energy can be thought of as the minimum amount of energy that exists between a set of reactants and the energy barrier that allows a reaction to proceed (78). Use of the term activation energy assumes that the mechanism of the reaction remains the same over a range of temperatures and degrees of hydrations. The hydration of cement and supplementary cementitious materials does not satisfy these criteria and cannot be considered one of these systems. Thus, the term "apparent" activation energy is used. The use of an apparent activation energy to describe hydration of cementitious materials, termed here as E_{a-hyd}, is well documented in the literature and typical values for most cements are around 36 kJ/mol to 40 kJ/mol (79,80).

The temperature and the activation energy of hydration can be used with a time increment, as shown in Equation 14, to determine the equivalent age.

$$t_{equivalent} = \sum_{o}^{t} \exp\left[\frac{-E_{a-hyd}}{R}\left(\frac{1}{T} - \frac{1}{T_o}\right)\right] \cdot \Delta t$$
$$= \sum_{o}^{t} \gamma\left(T, E_{a-hyd}\right) \cdot \Delta t \qquad (14)$$

where E_{a-hyd} is the parameter described as the apparent activation energy of hydration, R is the universal gas constant, T is the absolute temperature of the specimen, and T_o is an absolute reference temperature, taken as 23 °C (296 K) in the United States and Δt represents the calendar age of a specific time step, typically in days. For convenience, the exponential term can be consolidated to γ, which can be defined as the age multiplier and is dependent on the temperature, T, and the activation energy of hydration, E_{a-hyd}.

It should be noted that the age multiplier changes significantly at different temperatures and for different activation energies of hydration. For reference, Figure 7.4 shows the age multiplier for a range of standard activation energies of hydration for a wide range of temperatures. It should be noted that the age multiplier is function of activation energy and temperature, can vary with each time step, and should be applied to an incremental calendar time, not the total calendar time.

7.6 Early Age Considerations

Electrical testing has often been used to determine time of setting, e.g., (25,81), as a jump has been observed in resistivity. Sant et al. showed that this jump is mostly due to increases in temperature due to heat of hydration (82).

Additionally, it has been shown that at early ages, the pore solution in cementitious systems can exhibit a marked jump in resistivity (20,83). It is believed that this occurs primarily due to consumption of sulfates and release of additional hydroxide ions into the pore solution, but more study is needed to understand these effects. As such, it is cautioned that resistivity measurements in the first 36 h be interpreted carefully.

8. TEST CORRELATIONS

8.1 Correlation with Mixture Characteristics

For a saturated concrete, resistivity measurements are primarily a function of the microstructure, and specifically the porosity and its connectivity. A relationship is seen between water-to-cementitious materials ratio and electrical resistivity, as discussed by Henkenseifken et al. (84). The data, which were tested on mortar specimens, have been reproduced in Figure 8.1, in terms of resistivity.

Figure 7.4 Age multiplier, γ, for a series of different activation energies of hydration, E_{a-hyd}, and specimen temperatures, reproduced from (5).
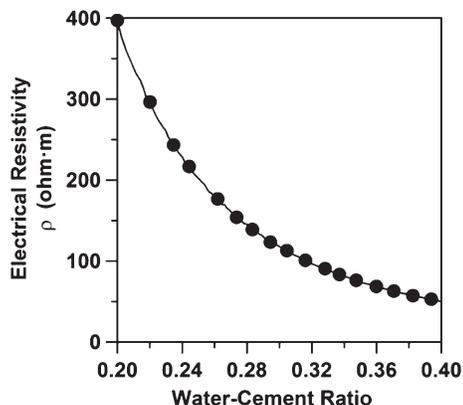
Figure 8.1 Influence of water-to-cementitious materials ratio on electrical resistivity of a type I OPC mortar, tested at 28 d, from (84).
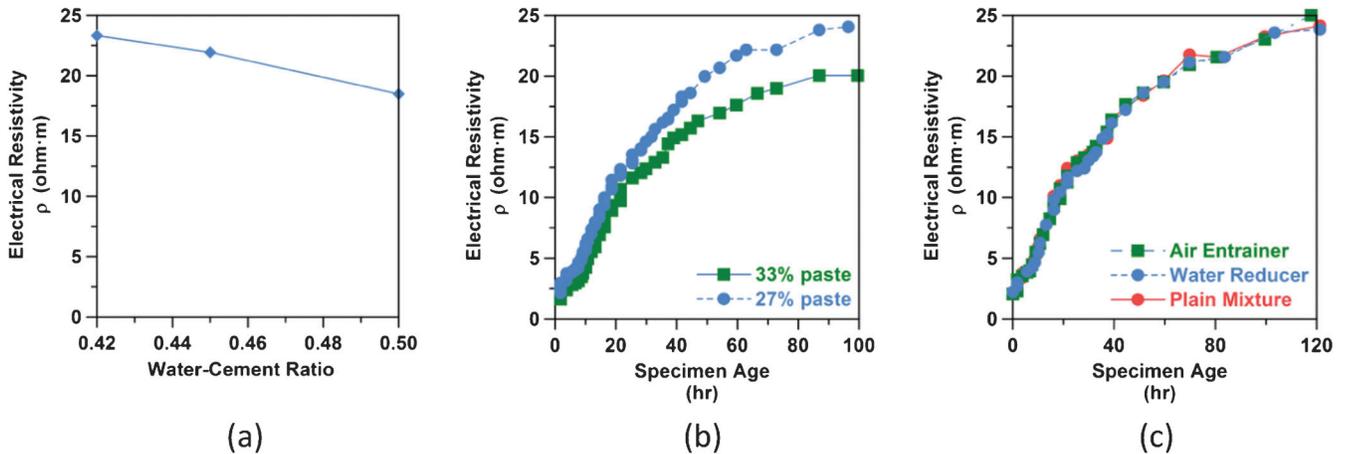
Figure 8.2 Data from Castro et al. (*43*), showing electrical measurement dependence on (a) water-to-cementitious materials ratio at 7 d, (b) paste content within the first 2 d and (c) use of chemical admixtures for concrete mixtures.

Castro et al. conducted a study using concrete mixtures, and has shown a similar dependence on water-to-cementitious materials ratio, as well as paste fraction (*43*). That study also highlighted the minimal effects of chemical admixtures, such as water reducers and air entertainers, on resistivity measurements (*43*); accelerators and corrosion inhibitors, conversely, are known to have large impacts on both pore solution and concrete specimen resistivity (*59*). Their results have been reproduced here in terms of resistivity, shown in Figure 8.2.

8.2 Correlation with Diffusion Measurements

In many cases, the results from a resistivity test are used as a method of assessing the transport properties, e.g., formation factor. Resistivity measurements are often preferred, as discussed previously, as they can be conducted much more rapidly than other test methods. However, other more robust test methods, e.g., an ionic diffusion test, have a series of inputs that allow for a more rigorous determination of true transport properties. A study by Spragg et al., available in (*5*), compared results from a resistivity test to an ionic diffusion test. The ionic diffusion test was a SIMCO Stadium approach, which uses a sealed cured specimen begins with a vacuum saturated specimen (*85*).

If the corrections discussed in Chapter 7 are neglected, and the measured resistivity is divided by the assumed resistivity of the pore solution resistivity at saturation, the apparent formation factor is obtained. This is shown in Figure 8.3, named the apparent formation factor.

The large differences in Figure 8.3 between the apparent formation factor measured from an ionic diffusion test and the resistivity indicate the need for the additional corrections proposed in Chapter 7.

For this study, the lime water and accelerated lime water specimens were assumed to have undergone leaching. For this mixture, Spragg approximated a linear relationship between the resistivity of the pore solution assuming no leaching and the equilibrium resistivity when the pore solution and the storage solution reach equilibrium (*5*). Using this approach, the resistivity of the pore solution was approximated to increase by a factor of nearly two due to leaching (*5*). The degree of saturation was measured at 90%. The pore solution-cured specimens had a zero leached fraction (based upon the approach taken by Spragg for a storage solution of pore solution) and were measured to have a degree of saturation of 90%. The sealed specimens had a zero leached fraction and were measured to have a degree of saturation of 74%. The vacuum saturated lime water specimens were assumed to be completely saturated (100% degree of saturation) with no leached fraction, as testing was performed 24 h after saturation was initiated. Lastly, the pore solution saturated specimens were assumed to be completely saturated, and the pore solution concentration was measured to be 1.6 times higher than the pore solution at saturation. This corresponds to a pore solution with twice the ionic strength, which upon oven drying and re-saturation with an artificial pore solution with the same ionic strength would lead to a solution in the pores that has double the ionic strength as the initial pore solution. When the corrections obtained in the previous section are used, the differences among the different curing conditions are reduced substantially, as shown in Figure 8.4. This results in a formation factor that is similar to the value provided from an ionic diffusion test.

8.3 Correlation with the Rapid Chloride Permeability Test

As mentioned previously, the rapid chloride permeability test (RCPT) is popular test that is commonly used to assess the chloride penetration resistance (*59*). This test involves monitoring the total charge passed across a two-inch (50 mm) thick specimen with a diameter of four-inches (100 mm) for a total of 6 h. First principles enable Ohms law and the relationship
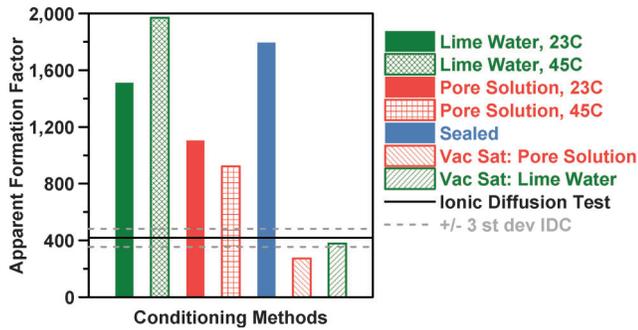
Figure 8.3 Formation factor obtained for measurements on a Class C concrete that are uncorrected. For reference, the formation factor obtained from the ionic diffusion test using the SIMCO Stadium approach is shown as a dotted line with a ± 3 standard deviation, from (5).
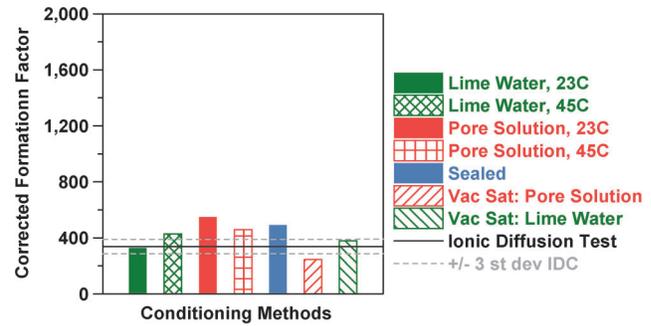
Figure 8.4 Formation factor obtained for measurements on a Class C concrete that are corrected using the approach described previously. For reference, the formation factor obtained from the ionic diffusion test using the SIMCO Stadium approach is shown as a dotted line with a ± 3 standard deviation, from (5).

between current and charge to be used to directly relate the total charge passed to the resistivity of the material. The ratio of voltage and resistance can be assumed to remain constant over the whole test period, and as the RCPT is a uniaxial test, the geometry factor can be given by the ratio of area to length. The test voltage of 60 V can be used to obtain ρ, which is expressed in units of $\Omega \cdot m$.

$$Q_{RCPT}[\text{coulombs}] = \int_0^{6hr} I \, dt = \frac{V}{\rho \cdot \frac{L}{A}} \int_0^{6hr} dt$$

$$= Q_{RCPT} = \frac{207000}{\rho[\text{ohm} \cdot \text{m}]} \quad (15)$$

Where Q_{RCPT} is the total charge passed over the 6 h time period, and ρ represents the resistivity of the material, in $\Omega \cdot m$. When using units of $k\Omega \cdot cm$, the numerator of Equation 15 should be modified to 20700. While reduced here to a single factor, the numerator of Equation 15 accounts for the geometry of the RCPT test specimen (two inch thick, four inch diameter) and the total charge passed with a 60 V potential. This relationship doesn't account for secondary effects, namely sample heating which is seen for low resistivity concrete

(11) or an increase in resistivity seen as chloride binding occurs (86). An additional source of error between RCPT and resistivity measurements can be attributed to both leaching and saturation, as the resistivity is measured and then specimens are cut and vacuum saturated using tap water before the RCPT test is conducted.

Many research studies have evaluated the relationship between resistivity and RCPT results, although most have used an experimental relationship between resistivity and results from an RCPT, instead of first principles. These have been included in Figure 8.5, with the references available in the list of references, including (87–92).

While the experimental fits from the various research studies do not exactly match the relationship from first principles, a reasonable agreement is noted. Figure 8.5 has also included a variation that can be obtained from the precision of the RCPT test, which ASTM C1202-12 gives as 42% for a single operator (59). One important observation is that while typically low values from RCPT are considered characteristic of high quality concrete, this corresponds to higher measurements from resistivity tests.

Using the first principles relationship, values of resistivity that are equivalent to RCPT limits can be
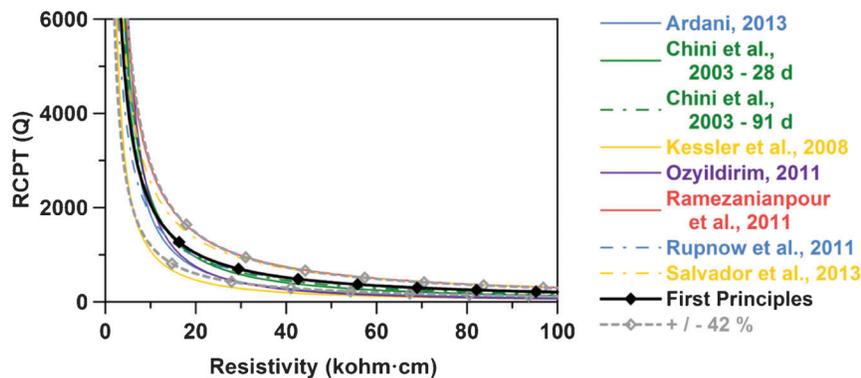
Figure 8.5 Correlation between rapid chloride permeability (total charge passed over 6 h) and resistivity, from (5).

TABLE 8.1
Performance limits from the RCPT, along with equivalent resistivity values of a saturated system, from (5)

ASTM C1202 Classification[1]	Charge Passed (Coulombs)[1]	Resistiviy (kOhm·cm)[2]
High	>4,000	<5.2
Moderate	2,000–4,000	5.2–10.4
Low	1,000–2,000	10.4–20.7
Very low	100–1,000	20.7–207
Negligible	<100	>207

[1]From ASTM C1202-12.
[2]Calculated using first principles.

calculated, as RCPT is a test that many practitioners understand well (34). These limits are shown in Table 8.1, along with the classification from the RCPT standard (59). It is important to highlight that this would be resistivity of a saturated system, which would necessitate correction for saturation if resistivity were measured on sealed specimens.

9. APPLICATIONS

9.1 Mixture Qualifications

Resistivity tests have the potential to be used as a mixture qualification tool. However, with the test's dependence on specimen conditioning, the development of performance limits for surface resistivity has presented technical challenges. A potentially more reliable approach may be to specify the Formation Factor, or a resistivity measurement normalized by the pore solution resistivity. The pore solution can be estimated using the chemistry of the cement or by pore solution extractions, although the first may be more desirable because it does not require laboratory measurement. Electrical measurements on sealed specimens could be obtained, with subsequent determination of their degree of saturation. This would allow for correction to a saturated state using the saturation function, outlined in Section 7.1.

9.2 Use as a Quality Control Tool

Another potential use of the resistivity test would be for use as a quality control tool. Resistivity has been shown to be highly dependent on the paste content and water content in a concrete mixture, both of which are of interest to a producer during the production stage of a concrete construction project. During the trial batch, resistivity measurements could be conducted. Upon subsequent approval of the trial batch, resistivity targets could be established using these resistivity measurements. The producer could then use these targets to ensure that production is similar or better than the approved trial batch.

For this application, the use of a sealed specimen would be suggested. This could be more desirable because of its simplicity and because it does not require

TABLE 9.1
Costs comparison of rapid chloride permeability test (RCPT) and surface resistivity, reproduced from Rupnow and Icenogle (38)

Test Method	Initial Equipment Costs (2011 USD)	Technician Hours per Test
Rapid chloride permeability test (RCPT, ASTM C1202)	18,000	8.0
Surface resistivity	2,800	0.3

a correction to account for leaching. However, in this case, it is important to prevent a specimen from drying to the atmosphere, so the use of a concurrent mass change criteria is also suggested.

9.3 Cost Comparison

Resistivity has the potential to provide a considerable costs savings, once implemented. Much of this savings will depend ultimately on how the test is implemented. One application would be the replacement of the rapid chloride permeability test (RCPT), similar to what was done by the Louisiana Department of Transportation and Development (LA DOTD).

A cost analysis was conducted by Rupnow and Icenogle, summarized in Table 9.1, considering surface resistivity as a replacement for RCPT, for use in quality assurance testing (38). This study considered equipment costs, the number of technician hours for testing and preparation, and the cost per test. Furthermore, the study considered a technician hourly cost rate of 23.38 USD in 2011.

Rupnow and Icenogle describe the LA DOTD testing of 480 lots of structural concrete for quality assurance purposes in the average year. For the LA DOTD, a lot of structural concrete typically consists of 200 yd^3 of concrete. The authors showed that a total cost in a typical year for the RCPT test was approximately 108,000 USD, while the surface resistivity test was about 6,500 USD. This would equate to a savings of nearly 100,000 USD in the first year of testing (38).

Furthermore, while these values are presented for quality assurance testing, Rupnow and Icenogle have shown that when used in a quality control application, savings could be in excess of 1.5 million USD (38).

10. SUMMARY AND CONCLUSIONS

These projects examined the potential for using electrical testing on concrete as a potential surrogate for obtaining information on ion and fluid transport. Electrical measurements are particularly attractive for use in quality control as they are easy to perform, are performed rapidly, and can be directly related to fluid transport. This work describes how electrical resistance measurements should be corrected for geometry to obtain a geometry-independent resistivity or conductivity. Further, this work reviews and

discusses several factors that influence the resistivity that is measured including porosity, pore connectivity, the role of temperature on degree of hydration (activation energy), temperature effects on conduction, ionic leaching, and the role of temperature and leaching on porosity. The goal of this work is to provide an overview of the main factors that should be considered when conducting electrical property testing, when using electrical properties for quality control/quality assurance, or if using these materials for acceptance. As a part of this project a series of testing devices were purchased and provided to the INDOT district testing labs for the purpose of providing training and providing information on the variability associated with testing. A round robin study has shown that a coefficient of variation of 4.36% was obtained leading to a within laboratory precision of 12.8% and a multi-laboratory precision of 36.0%. This work has shown that temperature can dramatically influence the resistivity. The work has shown that in general for a standard 100 mm × 200 mm test cylinder, the ratio of surface resistivity to uniaxial resistivity, specifically the factor $\hat{k}_2$ discussed in Section 5.1, is 1.9 for a homogenous material; however if the material is heterogeneous (due to drying or leaching) this value changes. This project has also illustrated the importance of ionic leaching. It was shown that accelerated curing requires temperature correction as well as control of ionic leaching. A direct correlation is discussed between electrical resistivity and the rapid chloride permeability test. At the current time, resistivity tests show promise in a quality control program, as a method of monitoring the variation associated with production. If used in this way, a trial batch could be used to develop target values, similar to that which is currently done with the maturity method. It is anticipated that an agency could eventually have the potential to use resistivity for mixture qualification; however, additional work is needed to correlate the resistivity with performance or service life models.

11. ACKNOWLEDGEMENTS AND DISCLAIMER

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- Spragg, R., J. Castro, T. Nantung, M. Paredes, and J. Weiss. Variability Analysis of the Bulk Resistivity Measured Using Concrete Cylinders. *Advances in Civil Engineering Materials*, Vol. 1, No. 1, 2012.

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- Draft Standard Method of Test for the Uniaxial Resistivity of a Concrete Cylinder. Submitted to the American Association of State Highway and Transportation Officials, Washington, D.C., 2013.

- Resistivity Training Session co-sponsored by Purdue Civil Engineering and the Office of Materials Management in January 2013, detailed here: https://engineering.purdue.edu/JTRP/news/training-for-concrete-resistivity-testing.

- Ongoing support to districts that are using resistivity tests.

About the Joint Transportation Research Program (JTRP)

On March 11, 1937, the Indiana Legislature passed an act which authorized the Indiana State Highway Commission to cooperate with and assist Purdue University in developing the best methods of improving and maintaining the highways of the state and the respective counties thereof. That collaborative effort was called the Joint Highway Research Project (JHRP). In 1997 the collaborative venture was renamed as the Joint Transportation Research Program (JTRP) to reflect the state and national efforts to integrate the management and operation of various transportation modes.

The first studies of JHRP were concerned with Test Road No. 1—evaluation of the weathering characteristics of stabilized materials. After World War II, the JHRP program grew substantially and was regularly producing technical reports. Over 1,500 technical reports are now available, published as part of the JHRP and subsequently JTRP collaborative venture between Purdue University and what is now the Indiana Department of Transportation.

Free online access to all reports is provided through a unique collaboration between JTRP and Purdue Libraries. These are available at: http://docs.lib.purdue.edu/jtrp

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