TECH**BRIEF**

ELECTRICAL RESISTIVITY TESTING TO RAPIDLY ASSESS THE DURABILITY OF UHPC-CLASS MATERIALS

FHWA Publication No.: FHWA-HRT-21-095

FHWA Contact: Robert P. Spragg, HRDI-10, ORCID: 0000-0001-9205-1486, 202-493-3233, robert.spragg@dot.gov. Ben Graybeal, HRDI-40, ORCID: 0000-0002-3694-1369, 202-493-3122, benjamin.graybeal@dot.gov.

TABLE OF CONTENTS

INTRODUCTION

Ultra-high performance concrete (UHPC) is a class of cement-based composite materials with enhanced properties as compared to conventional concrete. There is growing interest, both in the United States and worldwide, in using UHPC to address needs in the bridge sector (Graybeal et al. 2020). Appropriate use of UHPC must be founded on common definitions of minimum performance attributes. As with mechanical properties, durability properties also must be defined in terms of standardized test methods. This TechBrief presents an advancement toward using electrical resistivity as a rapid method to evaluate the durability of UHPC-class materials.

U.S. Department of Transportation
Federal Highway Administration

Research, Development, and Technology
Turner-Fairbank Highway Research Center
6300 Georgetown Pike
McLean, VA 22101-2296

https://highways.dot.gov/research

BACKGROUND

UHPC

Typically, UHPC consists of blended cementitious materials, well-graded fine granular constituents, a low water content, an appropriate chemical admixture system, and a high percentage of discontinuous internal fiber reinforcement. Currently, both commercial UHPC products and non-commercial UHPC mixture designs are available for use in the United States. Due in part to their enhanced mechanical and durability properties, UHPC-class materials have become popular for use in specific infrastructure construction over the last two decades.

UHPC can facilitate the use of accelerated bridge construction methodologies, specifically in connections for prefabricated bridge elements (Graybeal 2019). Also, the unique properties and capabilities of UHPC-class materials have been leveraged for use in bridge preservation and repair (FHWA 2020). UHPC-class materials are also being explored for use in primary structural elements. For example, constructing pretensioned bridge girders using UHPC can facilitate longer spans, fewer girder lines, and reduced dead loads (El-Helou and Graybeal 2019).

Available Test Methods for Assessing Durability

Conventional cement-based materials have standardized test methods for evaluating durability properties, including ASTM C666 – *Standard Test Method for Resistance of Concrete to Rapid Freezing and Thawing* (ASTM 2015), ASTM C1202 – *Standard Test Method for Electrical Indication of Concrete's Ability to Resist Chloride Ion Penetration* (ASTM 2019), ASTM C1556 – *Determining the Apparent Chloride Diffusion Coefficient of Cementitious Mixtures by Bulk Diffusion* (ASTM 2016a), and ASTM C1585 – *Standard Test Method for Measurement of Rate of Absorption of Water by Hydraulic Cement Concretes* (ASTM 2020).

The application of traditional durability tests to UHPC-class materials is complicated by two factors: first, the dense nature and low porosity of the cementitious matrix; and second, the presence of high volumes of fiber reinforcement. For example, longer chloride ponding times as described in ASTM C1556 might be needed in UHPC-class materials to achieve a measurable chloride penetration depth and allow for a proper determination of a diffusion coefficient. Also, many existing durability tests are index based, with indexes built around the performance of conventional cement-based materials. UHPCs can show results that are often negligible within the context of these tests (Provete Vincler et al. 2019; Graybeal and Tanesi 2007).

The selection of a method to assess the durability of UHPC-class materials requires that the method produce results that are indicative of the anticipated durability of the material and allow for implementation with a reasonable level of effort by the testing community. For many years, the conventional concrete community has utilized ASTM C1202 to this end. More recently, agencies have transitioned to electrical resistivity (FDOT 2021; LADOTD 2016).

Electrical resistivity is gaining popularity for four reasons. First, electrical resistivity is a rapid, nondestructive test that can be accomplished in partnership with other methods. Second, electrical resistivity can be accomplished with a minimal amount of equipment and training. Third, electrical resistivity has shown a strong correlation to durability (both through first principles and experimental studies). Fourth, electrical resistivity can be extended to material properties used in engineering models to understand service life (Spragg et al. 2013a; Weiss et al. 2017).

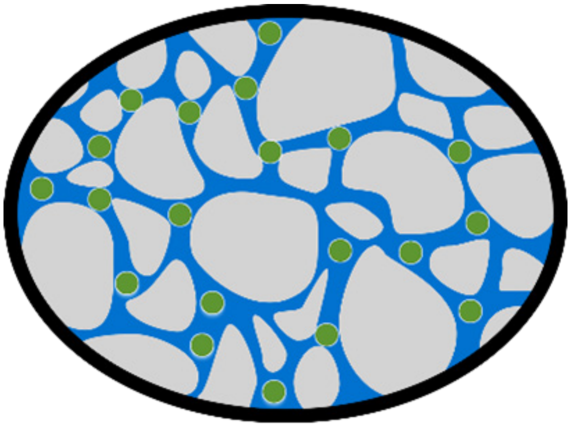
Background of Electrical Resistivity Testing

Electrical resistivity is a material property that indicates how easily electrical charge moves through a material when an electric field is applied. In cement-based materials, the movement of electric charge occurs primarily within the ionic pore solution (Rajabipour 2006). Electrical resistivity testing assumes the presence of a single conductive phase. Therefore, the presence of any alternative conductive phases (e.g., steel fibers or carbon fibers) can significantly alter the conductive path and result in lower resistivity measurements.

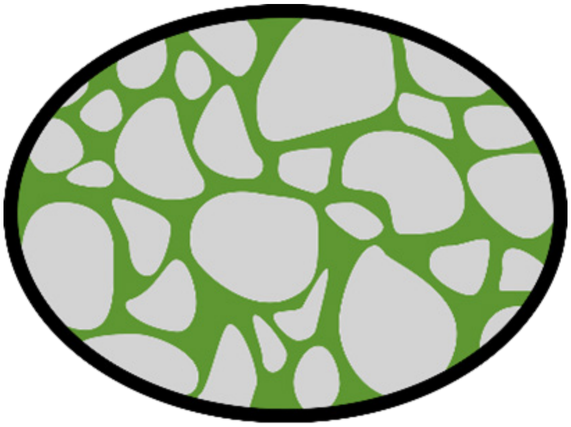
Electrical resistivity depends on three key parameters: the concentration and species of ions in the solution; the volume of the fluid within the material; and the connectivity of the fluid phase. These different parameters are demonstrated in figure 1. Figure 1-A demonstrates the role of the solution in the pores, figure 1-B highlights the role of the volume of the conductive fluid, and figure 1-C illustrates the role of the connectedness of the conductive fluid. At constant temperature and at moisture states typical of the method used in this study (i.e., following the procedures of AASHTO TP 119), the second and third parameters outlined in figure 1 are related to the quality of the microstructure (AASHTO 2021). Higher quality microstructure tend to result in higher resistivity values (Archie 1942).

Figure 1. Schematic.
Three key factors impacting electrical resistivity measurements in cement-based materials.

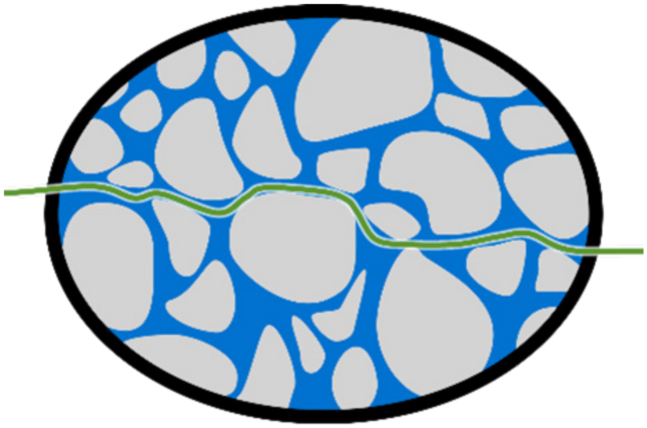
A. Ionic concentration and resistivity of the pore solution.



B. Volume of fluid filled pores.



C. Connectivity.



Source: FHWA.

Materials and Methods

A series of six proprietary, commercially available UHPC materials were used in the study. The UHPC materials are identified as U-A, U-B, U-C, U-D, U-E, and U-F. The UHPC materials consisted of preblended granular and powdered mixtures along with chemical admixtures that were mixed following recommendations and proportions from each manufacturer. Steel fibers are commonly added during the last stage in the mixing of these concretes. However, steel fibers were not added to the specimens tested for electrical resistivity.

Two conventional concretes categorized as class A4 and class A5 by the Virginia Department of Transportation (VDOT) standard specifications were also tested (VDOT 2016). The A4 concrete consisted of a water-to-cementitious material ratio (w/cm) of 0.43 by mass, 5.5-inch slump, and 5.5 percent entrained air volume. The A5 consisted of a w/cm of 0.40, 3-inch slump, and 3.7 percent entrained air volume. The concretes were made with Type I/II ordinary portland cement, supplementary cementitious materials (SCM), and local aggregates that met the specifications of VDOT Standard Specifications. The concrete mixtures had compressive strengths of at least 4 kips per square inch (ksi) (A4) and 5 ksi (A5) at an age of 28 d as specified in VDOT standard specifications.

Compressive Strength

UHPC materials were evaluated for strength using standard 3-inch-diameter by 6-inch-tall cylinders, which were prepared and tested as described in ASTM C1856 (ASTM 2017). For compressive strength testing, steel fibers were included in the UHPC materials. The A4 and A5 concretes were evaluated using standard 4-inch-diameter by 8-inch-tall cylinders using ASTM C39 (ASTM 2016b).

Compressive strength was tested at an age of 1, 3, 7, 14, 21, and 28 d. Three cylinders were made per testing age. Specimens were made and allowed to cure in their molds, demolded at time of compressive strength testing, and prepared and tested for strength in accordance with the relevant standard test method.

The UHPC materials tested presented a range of compressive strengths from 18.3 ksi to 24.1 ksi at 28 d. The conventional concrete specimens achieved a strength at 28 d of 4.4 ksi for the A4 class and 5.6 ksi for the A5 class.

Electrical Resistivity

The conventional concretes were evaluated for resistivity using standard 4-inch-diameter by 8-inch-tall cylinders, and the UHPCs were evaluated using standard 3-inch-diameter by 6-inch-tall cylinders. A set consisted of three cylinders for each mixture.

The uniaxial resistivity was determined in accordance with AASHTO TP 119 – *Standard Method of Test for Electrical Resistivity of a Concrete Cylinder Tested in a Uniaxial Resistance Test* (AASHTO 2021). Specimens were mixed and cast following manufacturer recommendations (with steel fibers excluded) and demolded within 48 h from the time of mixing.

Upon demolding, specimens were measured for diameter and length, and sets of three specimens were each placed into one of two curing solutions. The first was a traditional curing solution consisting of saturated calcium hydroxide (commonly known as lime-saturated solution or limewater). The second was an alkali curing solution outlined in TP 119-21 known as conditioning option A (consisting of potassium hydroxide, sodium hydroxide, and calcium hydroxide). Each set of specimens was submerged in a bucket of the relevant solution. The solution depth above the top of the specimens was approximately 1.5 inches.

At testing ages of 1, 7, 14, 21, 28, 56, and 91 d, the specimens were removed from the conditioning solution, wiped to a surface-dry condition using a dry cloth, tested for mass, tested for temperature using a noncontact infrared thermometer, and tested for uniaxial resistance using an AC resistance meter. The measured resistance value (unit of ohms, denoted as Ω) was multiplied by the ratio of cross-sectional area to length (unit of meters, denoted as m) to determine the uniaxial resistivity (unit of ohm meter, denoted as Ω·m).

For standard test cylinders, the ratio of area to length can be taken as 0.03 m for 3 × 6 and 0.04 m for 4 × 8. Nonstandard specimen sizes can also be used in this test, assuming a cylindrical section, through the calculation of the corresponding cross-sectional area-to-length ratio. Note that U.S. customary units of measurement for resistivity are considered nonstandard, thus SI units are used here. An example of the uniaxial resistivity test setup is shown in figure 2.

Figure 2. Photograph. Example test setup to determine electrical resistivity using the uniaxial resistivity test method, AASHTO TP 119, on a standard 3-inch by 6-inch cylinder of UHPC.

Source: FHWA.

RESULTS

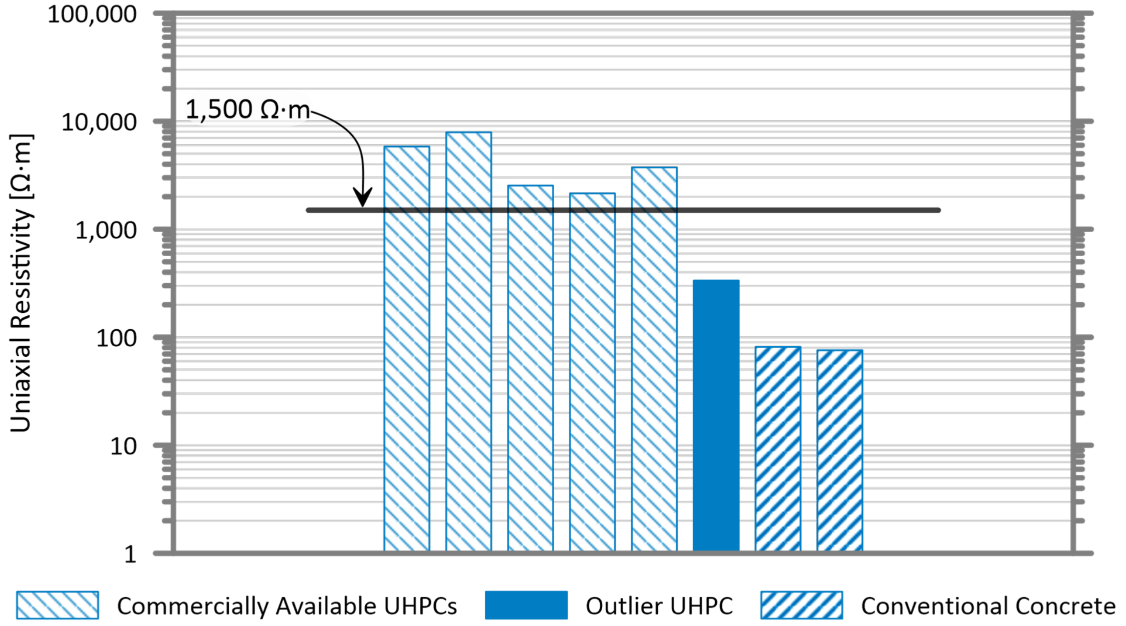
Uniaxial Resistivity at an Age of 28 d

The materials evaluated as a part of this study represent many of the commercially available, preblended UHPCs in the U.S. market, and they give a reasonable picture of the range of values that might be encountered when engaging UHPC-class materials. These measured values tested in accordance with AASHTO TP 119-21 and the discussion provided herein can be used to propose a threshold index on resistivity measurements. The threshold index can then be used for the purpose of identifying a UHPC-class material.

The minimum value observed in the UHPCs at an age of 28 d was 2,150 Ω·m. Considering anticipated variation associated with multiple operators at different laboratories, as well as the fact that this study only included a sample of the UHPC-class materials available on the market, a threshold of 1,500 Ω·m was selected.

Figure 3 is annotated with this value to demonstrate where it falls within the data captured in this study. One UHPC exhibited a resistivity value at the 28-d testing age that was 7 percent of the average resistivity of the remaining UHPCs. A lower value compared to other UHPCs could be a function of a different pore structure or the presence of other conductive phases in this UHPC or both. Based on a low value compared to other UHPCs, this UHPC was considered an outlier and was not included in any additional analysis. The performance of this UHPC is relevant in the context of alternative test methods presented in the Discussion portion of this document.

Figure 3. Bar Graph. Resistivity values of UHPCs and conventional concrete specimens at an age of 28 d, tested in TP 119-21 curing solution using meter A.



Source: FHWA.

Role of Testing Parameters on Resistivity Measurements of UHPCs

When conducting the test, particular attention should be made to the details of the test method and any supplemental details that a specification might include. While a series of these details have been developed for conventional concretes, they have not necessarily been developed for UHPCs (Spragg et al. 2013a; Spragg et al. 2013b; Rupnow and Icenogle 2014; Andrade, Castellote, and D'Andrea 2011; Mosavi et al. 2020). This section will highlight the role these parameters play in affecting values of resistivity that might be measured in UHPCs. Results from a year-long laboratory study are used to illuminate the discussion.

Resistivity Development with Time

At an age of 28 d, resistivity values in UHPCs are distinctly different than those of conventional concrete. As the materials continue to age, their resistivity will increase. However, 28 d seems to provide a sufficient period of evaluation to see distinctions between UHPCs and conventional concrete.

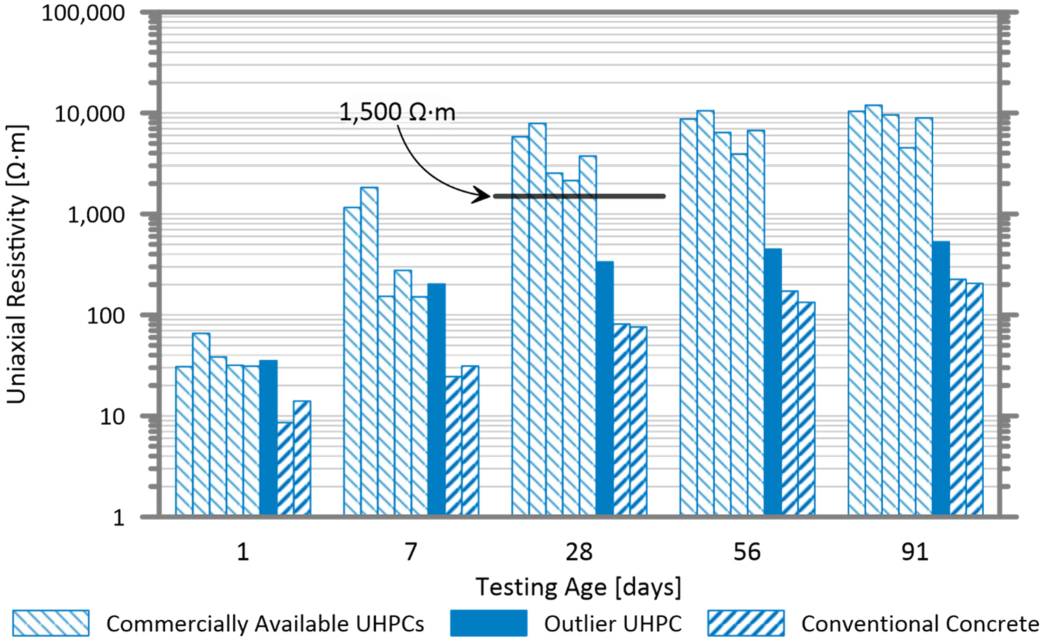
As cement-based materials undergo hydration and pozzolanic reactions, the microstructure develops and densifies over time. These changes increase the materials' resistivity values. In this study, the resistivity values of conventional concretes increased on average by a factor of 7 between 1 d and 28 d and by an average factor of 20 between 1 d and 91 d.

Resistivity values of UHPCs increased on average by a factor of 90 between 1 d and 28 d and by an average factor of 250 between 1 d and 91 d. As seen in figure 3 for conditioning in TP 119 curing solution, the resistivity of UHPCs can be similar to that of conventional concretes at early testing ages. However, at 28 d, the resistivity in the UHPC was found to be between 25 and 90 times greater than that observed in the conventional concretes. At 91 d, the resistivity in the UHPC was found to be between 20 and 50 times greater than that observed in the conventional concretes.

The outlier UHPC highlighted previously only increased by a factor of 15 between the ages of 1 d and 91 d, and at an age of 91 d the resistivity was only about twice that of the conventional concretes.

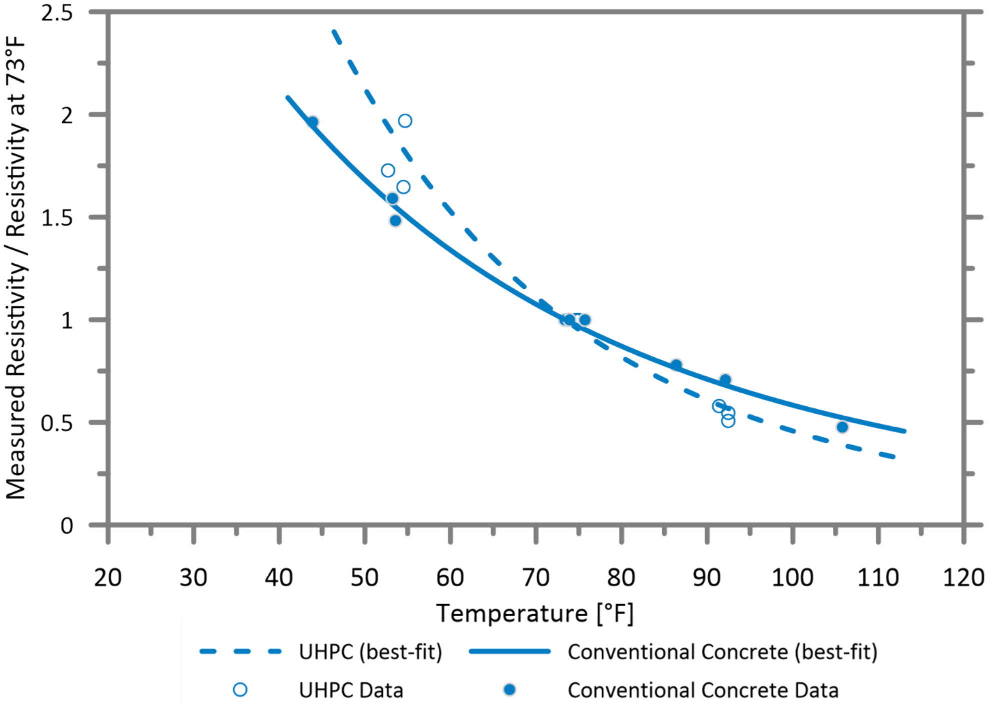
Looking at the 28-d measured values as a baseline to predict later-age properties, resistivity appear to change less in UHPCs than in conventional concretes. While evaluation at later ages is key for materials with large amount of SCMs, the effect of aging after 28 d is a lower percentage change in UHPCs than in conventional concretes. This distinction could be attributable to space limitations on hydration products and low moisture transfer, leading to desiccation that prevents water from participating in additional hydration or pozzolanic reactions.

Figure 4. Bar Graph. Development of resistivity as a function of curing time for UHPCs and conventional concrete specimens in accordance with TP 119-21, with the 1,500 Ω·m threshold as identified in uniaxial resistivity at an age of 28 d subsection.



Source: FHWA.

Figure 5. Scatterplot. Temperature sensitivity of electrical measurements on UHPCs and conventional concretes, where data points represent measured values and lines represent best fit lines based on an activation energy of conduction.



Source: FHWA.

Temperature Sensitivity

Electrical measurements in cement-based materials have long been recognized to be temperature dependent, with higher temperatures leading to lower resistivity values (Sant, Rajabipour, and Weiss 2008).

Figure 5 highlights measured data and best-fit lines using an activation energy of conduction approach (Coyle et al. 2018). Typical activation energies of conduction for conventional concretes range from 15 to 20 kJ/mol·K; the UHPCs measured in this study demonstrate a best fit of 40 ± 4 kJ/mol·K. The larger value of activation energy of conduction means that UHPCs are more temperature sensitive than conventional concretes with respect to electrical resistivity measurements.

AASHTO TP 119 specifies the temperature at time of testing be kept within 73 ± 4°F and conventional concretes within this range exhibit a variation of about 5 percent. For UHPCs, it was observed this variation increased to 11 percent. This finding highlights the need to measure the temperature of the specimen at time of testing and to use caution if comparing resistivity values measured at different temperatures.

Conditioning Solution

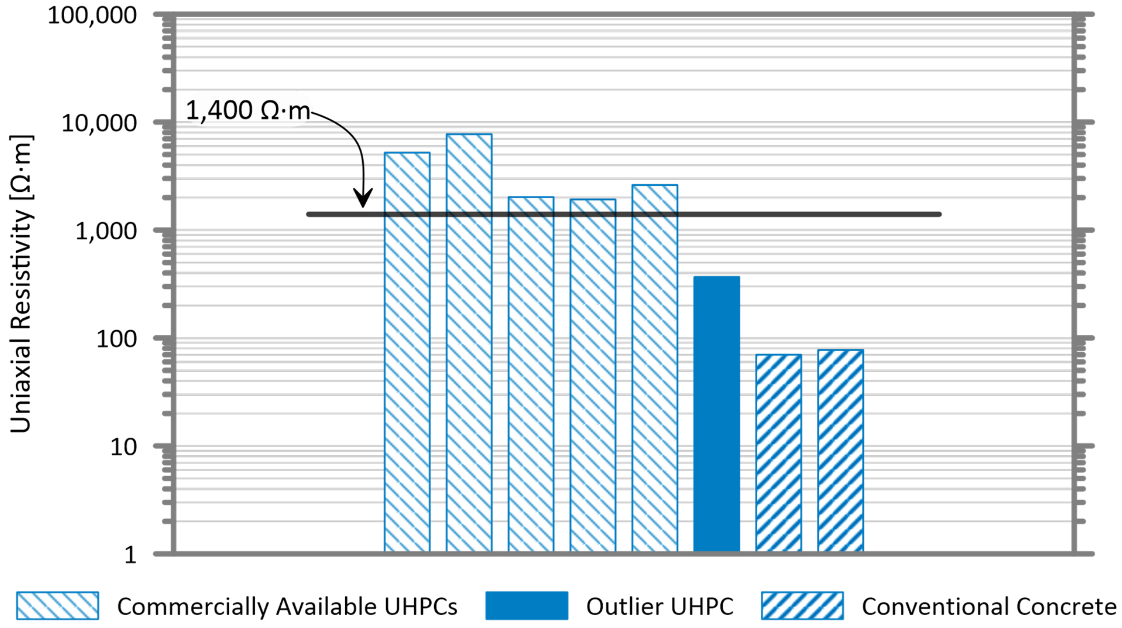
AASHTO TP 119-21 uses a moist curing methodology, and at the time of publication of this document it specifies curing in an alkali solution that is designed to mimic the pore fluid of typical cement-based materials. This methodology can help minimize alkali leaching but can also benefit the hydration and pozzolanic reactions in cement-based materials (Bu and Weiss 2014; Spragg et al. 2017). There seems to be some hesitation on the part of industry and owner agencies to adopt this curing solution. The hesitation is most likely attributable to the somewhat increased burden associated with maintaining the chemicals and risks associated with making, handling, using, and disposing of an alkaline solution.

With consideration of how this conflict might ultimately be resolved and considering the option of using a lime-saturated solution (i.e., limewater) as commonly used in the concrete industry for curing specimens, additional specimens were cured in lime-saturated solution.

While curing condition demonstrated an effect on measured test specimen resistivity, the effect was not consistent. Specifically, lime-saturated curing increased resistivity in some materials while it decreased resistivity in others. On average, across all the measurements conducted on UHPCs in this study, an average absolute difference of 8.8 percent between specimens cured in different solutions was observed.

Figure 6 illustrates values measured at 28 d in a lime-saturated solution. Similar to results shown in figure 3, an outlier UHPC was observed whose resistivity was only 7 percent of the average value of the other UHPCs. This material was excluded from further analysis. The minimum value from the remaining UHPCs was 1,920 Ω·m.

Figure 6. Bar Graph. Resistivity values of UHPCs and conventional concrete specimens at an age of 28 d, tested in lime-saturated solution using meter A.



Source: FHWA.

Considering anticipated variation associated with multiple operators at different laboratories, as well as the fact that this study only included a subset of the UHPC-class materials available on the market, a threshold of 1,400 Ω·m would be appropriate for UHPCs cured in lime saturated solution. Figure 6 is annotated with this value to demonstrate where it falls within the data captured in this study.

Testing Equipment

Two different pieces of equipment were used in this study to measure test specimen resistance, with the result then used to calculate the corresponding resistivity. These two pieces of equipment were chosen for this study because they represent different levels of equipment sophistication, with an economical field unit using a fixed, low frequency of 82 Hz (meter A) versus a higher-end scientific device tested at a frequency of 1 kHz (meter B). Results from UHPCs shown in figure 7 indicate meter B demonstrates results an average of 5 percent lower than measurements obtained from meter A. Aside from the results presented in this paragraph, meter A was used exclusively in this study.

Additional Observations That Impact Resistivity in UHPCs

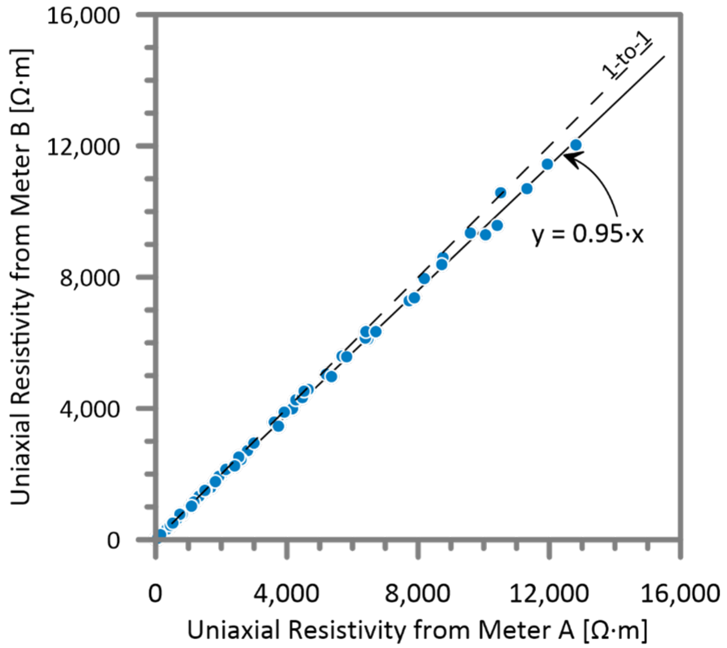
Manufacturers recommend a shelf life for preblended UHPC dry constituents. These constituent materials can chemically react with moisture in the air, and they can also contain materials with unstable phases whose performance in a freshly mixed concrete will degrade with time. To a certain extent, this sensitivity of constituents to age exists with conventional materials as well (De la Varga 2013).

The present study demonstrated resistivity values measured at an age of 28 d on specimens made with a preblend received shortly after manufacture (less than 1 mo) were 20 percent higher than values from the same preblend after it aged in dry storage at Turner-Fairbank Highway Research Center. In the latter case, specimens were made 12 mo from the manufacturing date of the preblend. This constituent aging effect has been observed in multiple systems, and more research is currently ongoing to further investigate this topic.

The standard TP 119-21 test method also highlights the importance of testing the specimen in a prewetted, surface-dry state. The presence of surface moisture, even a trace amount remaining after wiping with a damp rag or excess moisture from sponges used on electrodes, can reduce the measured resistivity, producing results that are not indicative of material performance. While this effect of surface moisture applies to conventional concretes as well, it was observed to be more significant for UHPCs.

Lastly, when conducting an electrical-based test (e.g., resistivity, ASTM 1202) on a material to assess microstructure, the key assumption is that the only conductive phase is the liquid pore solution.

Figure 7. Scatterplot. Comparison between two different pieces of equipment to determine the electrical resistivity, with meter B showing results an average of 5 percent lower than values obtained from meter A (best-fit-line: $y = 0.95 \cdot x$; $R^2 = 0.99$).



Source: FHWA.

The presence of other conductive phases (e.g., fibers, inclusions, or even admixtures that might be conductive) could make the application of electrical-based testing to assess microstructure a poor choice. In this study, the fibers were excluded from the materials when mixing.

Prior results have indicated negligible differences between penetration measured on UHPCs with and without fibers[1](Spragg et al. 2018). Other studies have demonstrated assessment without fibers provides conservative values compared to assessment with fibers (Provete Vincler et al. 2019). In cases where the conductive inclusion cannot be removed, an alternative evaluation might be necessary.

DISCUSSION

Electrical resistivity tests of cementitious materials can be conducted rapidly and are related to the pore structure, and more generally the durability, of the material. Among the wide range of test methods to measure resistivity, AASHTO TP 119 – *Standard Method of Test for Electrical Resistivity of a Concrete Cylinder Tested in a Uniaxial Resistance Test* was selected (AASHTO 2021).

TP 119 values typical of UHPCs were able to be measured with multiple pieces of commercially available equipment, while tests of UHPC samples conducted through other test methods (e.g., surface resistivity) were out of range for common testing equipment. This study used 3-inch-diameter by 6-inch long cylinders for uniaxial resistivity testing, but of chemical admixtures, and the variables associated with the chemistries of the composite preblend material.

The bounds of the assumptions on pore solution resistivity (ranging from 0.01 to 0.6 Ω·m) indicate the threshold proposed for UHPC resistivity of 1,500 Ω·m would correspond to an effective diffusion coefficient in the range of 4.2×10^{-14} to 7.6×10^{-13} m^2/s. Additional work is ongoing to extend resistivity measurements to other measurable parameters that might serve as inputs to lifecycle analysis.

While resistivity testing can be conducted easily, other durability tests are being explored. Research has been directed toward evaluation of a screening tool, or a technique, that can predict service life, or an appropriate test that addresses cases where a material may contain conductive inclusions. In cases of conductive inclusions that cannot be removed from the material, electrical tests should be applied with caution. If the inclusions are an integral part of the matrix required for workability or to ensure reaction of the constituents, an alternative method of evaluation might be required.

Ongoing research is looking at alternatives to electrical-based tests, specifically an absorption test (ASTM C1585) and a chloride ponding test (ASTM C1556). Chloride migration could also be a test worth investigating, and literature has suggested modifications to standard methods for conventional concretes that would improve their applicability to UHPCs (Provete Vincler et al. 2019).

CONCLUSIONS AND RECOMMENDATIONS

Conclusions and recommendations from this study related to the use of electrical resistivity as a screening tool for the durability classification of UHPC-class materials are as follows:

- Electrical resistivity testing is gaining popularity by many owner agencies for use in durability evaluation of cement-based materials. Testing can be conducted economically with a minimal amount of specialized equipment or knowledge. Specimen preparation is much easier than comparable tests, and testing protocols can follow existing standard test methods (albeit without the inclusion of fibers in the material).
- AASHTO TP 119-21 – Standard Method of Test for Electrical Resistivity of a Concrete Cylinder Tested in a Uniaxial Resistance Test, was investigated and found to provide a robust testing framework (AASHTO 2021). Specimen geometry correction factors can be easily implemented, and testing equipment vendors can supply meters capable of testing UHPC-class materials.
- AASHTO TP 119-21 specifies curing specimens in an alkali curing solution. At the prescribed testing age, specimens are removed from the curing solution, towel dried to a surface-dry state, measured for temperature using a noncontact infrared thermometer to ensure the temperature is within 73 ± 4°F and tested for electrical resistance. The electrical resistance is multiplied by the ratio of cross-sectional area to length (in units of meters) to determine the uniaxial electrical resistivity in units of ohm meter (Ω·m).
- The presence of metallic fibers and other conductive inclusions can decrease the electrical resistivity and thus presents challenges when interpreting electrical measurements for durability evaluation. In cases where the conductive inclusion cannot be removed, alternative evaluation criteria are recommended. More work is forthcoming on other tests that might be applicable in these situations.

---

[1] Spragg, R. P., I. De la Varga, N. Saladi, A. Poursaee, and B. A. Graybeal. 2022. "Chloride Penetration and Corrosion in Closure Pours." (Forthcoming).

- Literature for conventional concrete has shown resistivity to be inversely proportional to a measure of diffusion and proportional to an estimated time to corrosion initiation. Care should be taken in extending the same understanding to UHPCs, as the low porosity can make electrical resistivity measurements of UHPCs more sensitive to chemistries affecting pore solution properties and small changes in pore network connectivity. The large range of values observed in tests of UHPC do not manifest in other durability tests. Care should be taken not to interpret resistivity differences between two UHPCs as being indicative of durability differences. Specifically, if one UHPC presents a resistivity double that of another, it does not mean it is twice as durable. While more data are forthcoming, the use of electrical resistivity to evaluate UHPCs should be understood as a threshold measurement indicative of whether the tested material has a cementitious matrix similar to other UHPCs.
- A resistivity threshold of at least 1,500 Ω·m at an age of 28 d obtained in accordance with AASHTO TP 119-21 using conditioning option A appears sufficient to distinguish UHPC-class materials from conventional concretes. This finding was based upon a survey of commercially available, preblended UHPCs available in the North American market as of 2020.
- A resistivity threshold of at least 1,400 Ω·m tested in accordance with AASHTO TP 119-21, with the modification of curing solution to lime-saturated solution, appears sufficient to distinguish UHPC-class materials from conventional concretes. While not explicitly allowed under AASHTO TP 119-21, it is a common curing method for concrete specimens. Results indicate that curing can influence resistivity results (i.e., test results for a material might be higher or lower in lime-saturated solution versus in the TP 119-21 curing solution), but on average the readings across the set of tested materials are similar between the specified curing solution and the lime-saturated solution.

REFERENCES

AASHTO. 2021. *Standard Method of Test for Electrical Resistivity of a Concrete Cylinder Tested in a Uniaxial Resistance Test.* AASHTO TP 119-21. Washington, DC: American Association of State Highway and Transportation Officials.

Andrade, C. 2018. "Design and Evaluation of Service Life through Concrete Electrical Resistivity." *Revista ALCONPAT* 8, no. 3: 264–279. https://doi.org/10.21041/ra.v8i3.349, last accessed July 29, 2021.

Andrade, C., M. Castellote, and R. D'Andrea. 2011. "Chloride Aging Factor of Concrete Measured by Means of Resistivity." Presented at the International Conference on Durability of Building Materials and Components. Porto, Portugal: Faculdade de Engenharia da Universidade do Porto Edicoes, p. 1–8.

Andrade, C., R. D'Andrea, and N. Rebolledo. 2014. "Chloride Ion Penetration in Concrete: The Reaction Factor in the Electrical Resistivity Model." *Cement and Concrete Composites* 47: 41–46. https://doi.org/10.1016/j.cemconcomp.2013.09.022, last accessed July 29, 2021.

Archie, G. E. 1942. "The Electrical Resistivity Log as an Aid in Determining Some Reservoir Characteristics." *Petroleum Technology* 146, no. 1: 54–62. https://doi.org/10.2118/942054-G, last accessed July 29, 2021.

ASTM. 2019. *Standard Test Method for Electrical Indication of Concrete's Ability to Resist Chloride Ion Penetration.* C1202. West Conshohocken, PA: ASTM International. https://doi.org/10.1520/C1202-19, last accessed July 29, 2021.

ASTM. 2016a. *Determining the Apparent Chloride Diffusion Coefficient of Cementitious Mixtures by Bulk Diffusion.* C1556. West Conshohocken, PA: ASTM International. https://doi.org/10.1520/C1556-11AR16, last accessed July 29, 2021.

ASTM. 2020. *Standard Test Method for Measurement of Rate of Absorption of Water by Hydraulic Cement Concretes.* C1585. West Conshohocken, PA: ASTM International. https://doi.org/10.1520/C1585-20, last accessed July 29, 2021.

ASTM. 2017. *Standard Practice for Fabricating and Testing Specimens of Ultra-High Performance Concrete.* C1856. West Conshohocken, PA: ASTM International. https://doi.org/10.1520/C1856_C1856M-17, last accesssed July 29, 2021.

ASTM. 2016b. *Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens.* C39. West Conshohocken, PA: ASTM International. https://doi.org/10.1520/C0039_C0039M-18, last accessed July 29, 2021.

ASTM. 2015. *Standard Test Method for Resistance of Concrete to Rapid Freezing and Thawing.* C666.

West Conshohocken, PA: ASTM International. https://doi.org/10.1520/C0666_C0666M-15, last accessed July 29, 2021.

Bu, Y., and J. Weiss. 2014. "The Influence of Alkali Content on the Electrical Resistivity and Transport Properties of Cementitious Materials." *Cement and Concrete Composites* 51: 49-58. https://doi.org/10.1016/j.cemconcomp.2014.02.008, last accesed July 29, 2021.

Coyle, A. T., R. P. Spragg, P. Suraneni, A. N. Amirkhanian, and W. J. Weiss. 2018. "Comparison of Linear Temperature Corrections and Activation Energy Temperature Corrections for Electrical Resistivity Measurements of Concrete." *Advances in Civil Engineering Materials* 7, no. 1: 174–187. https://doi.org/10.1520/ACEM20170135, last accessed July 29, 2021.

De la Varga, I. 2013. "Increased Fly Ash Volume and Internal Curing in Concrete Structures and Pavements." PhD dissertation. Purdue University.

El-Helou, R., and B. A. Graybeal. 2019. "The Ultra Girder: A Design Concept for a 300-Foot Single Span Prestressed Ultra High-Performance Concrete Bridge Girder." Proceedings of the 2nd International Interactive Symposium on Ultra-High-Performance Concrete. Albany, New York. Iowa State University Digital Press. https://doi.org/10.21838/uhpc.9707, last accessed July 29, 2021.

FDOT. 2021. "Standard Specifications for Road and Bridge Construction." Tallahassee, FL: Florida Department of Transportation. https://www.fdot.gov/programmanagement/implemented/specbooks/default.shtm, last accessed July 29, 2021.

FHWA. 2020. "UHPC for Bridge Preservation and Repair" (web page). https://www.fhwa.dot.gov/innovation/everydaycounts/edc_6/uhpc_bridge_preservation.cfm, last accesssed July 29, 2021.

Graybeal, B., E. Brühwiler, B-S Kim, F. Toutlemonde, Y. L. Voo, and A. Zaghi. 2020. "International Perspective on UHPC in Bridge Engineering." *Journal of Bridge Engineering* 25, no. 11. https://doi.org/10.1061/(ASCE)BE.1943-5592.0001630, last accessed July 29, 2021.

Graybeal, B., and J. Tanesi. 2007. "Durability of an Ultrahigh-Performance Concrete." *Journal of Materials in Civil Engineering* 19, no. 10. https://doi.org/10.1061/(ASCE)0899-1561(2007)19:10(848), last accessed July 29, 2021.

Graybeal, B.A. 2019. *Design and Construction of Field-Cast UHPC Connections*. Report No. FHWA-HRT-19-011. McLean, VA: Federal Highway Administration.

Halamickova, P., R. J. Detwiler, D. P. Bentz, and E. J. Garboczi. 1995. "Water Permeability and Chloride Ion Diffusion in Portland Cement Mortars: Relationship to Sand Content and Critical Pore Diameter." *Cement and Concrete Research* 25, no. 4: 790–802. https://doi.org/10.1016/0008-8846(95)00069-O, last accessed July 29, 2021.

LADOTD. 2016. "Louisiana Standard Specifications for Roads and Bridges." (web page) Baton Rouge, LA. http://wwwsp.dotd.la.gov/Inside_LaDOTD/Divisions/Engineering/Standard_Specifications/Pages/Standard Specifications.aspx, last accesssed July 29, 2021.

Mosavi, H., R. Alrashidi, M. Almarshoud , M. H. Alyami, , K. A. Riding, , C. C. Ferraro, M. D. A. Thomas, and H. DeFord. 2020. "Use of Electrical Test Method on Determination Aging Factor of Concrete Incorporating Supplementary Cementitious Materials." *RILEM Bookseries* 22: 299–306. https://doi.org/10.1007/978-3-030-22034-1_34, last accesssed July 29, 2021.

Provete Vincler, J., T. Sanchez, V. Turgeon, D. Conciatori, and L. Sorelli. 2019. "A Modified Accelerated Chloride Migration Tests for UHPC and UHPFRC with PVA and Steel Fibers." *Cement and Concrete Research* 117: 38–44. https://doi.org/10.1016/j.cemconres.2018.12.006, last accessed July 29, 2021.

Rajabipour, F. 2006. "Insitu Electrical Sensing and Material Health Monitoring in Concrete Structures." PhD dissertation. Purdue University.

Rupnow, T. D., and P. J. Icenogle. 2014. "Investigation of Factors Affecting PCC Surface Resistivity through Ruggedness Testing." *Journal of Testing and Evaluation* 42, no. 2: 467–474. https://doi.org/10.1520/JTE20130154, last accessed July 29, 2021.

Sant, G., F. Rajabipour, and W. J. Weiss. 2008. "The Influence of Temperature on Electrical Conductivity Measurements and Maturity Predictions in Cementitious Materials during Hydration." *Indian Concrete Journal* 82, no. 4: 7–16.

Spragg, R. P., Y. Bu, K. A. Snyder, D. P. Bentz, and J. Weiss. 2013a. "Electrical Testing of Cement-Based Materials: Role of Testing Techniques, Sample Conditioning, and

Accelerated Curing." Report No. FHWA/IN/JTRP-2013/28. Joint Transportation Research Program, Indiana Department of Transportation, and Purdue University: West Lafayette, IN. https://doi.org/10.5703/1288284315230, last accessed July 29, 2021.

Spragg, R. P., S. Jones, Y. Bu, Y. Lu, D. P. Bentz, K. A. Snyder, and W. J. Weiss. 2017. "Leaching of Conductive Species: Implications to Measurements of Electrical Resistivity." *Cement and Concrete Composites* 79: 94–105. https://doi.org/10.1016/j.cemconcomp.2017.02.003, last accessed July 29, 2021.

Spragg, R.P., I. De la Varga, L. Montanari, and B. Graybeal. 2019. "Using Formation Factor to Define the Durability of Ultra-High Performance Concrete." In 2nd International Interactive Symposium on Ultra-High Perfomrance Concrete. Iowa State University: Albany, NY. https://doi.org/10.21838/uhpc.9696, last accessed July 29, 2021.

Spragg, R. P., De la Varga, I., Nickel, C. A., B. A. Graybeal, and A. Poursaee. 2018. "Chloride Ingress and Corrosion in UHPC Closure Pours." Presentation at Spring 2018 ACI Convention: Salt Lake City, UT.

Spragg, R.P., C. Villani, K. A. Snyder, D. P. Bentz, J. W. Bullard, and W. J. Weiss. 2013b. "Factors That Influence Electrical Resistivity Measurements in Cementitious Systems." *Transportation Research Record* 2342, no. 1: 90–98. https://doi.org/10.3141/2342-11, July 29, 2021.

VDOT. 2016. *2016 Road and Bridge Specifications.* Virginia Department of Transportation: Richmond, VA. www.virginiadot.org/business/resources/const/VDOT_2016_RB_Specs.pdf, last accessed July 29, 2021.

Weiss, J., T. J. Barrett, C. Qiao, and H. Todak. 2016. "Toward a Specification for Transport Properties of Concrete Based on the Formation Factor of a Sealed Specimen." Presented at the *Transportation Research Board 95th Annual Meeting.* Washington, DC.

Weiss, W.J., R. P. Spragg, O. B. Isgor, M. Tyler Ley, and T. Van Dam. 2017. "Toward Performance Specifications for Concrete: Linking Resistivity, RCPT and Diffusion Predictions Using the Formation Factor for Use in Specifications." Presented at the *High Tech Concrete: Where Technology and Engineering Meet - Proceedings of the 2017 Fib Symposium.* https://doi.org/10.1007/978-3-319-59471-2_235, last accessed July 29, 2021.

Researchers—This study was performed by FHWA's Office of Infrastructure Research and Development by Robert Spragg and Ben Graybeal and also under contract DTFH6117D00017 by researchers Naveen Saladi, Luca Montanari, and Igor De la Varga.

Distribution—This TechBrief is being distributed according to a standard distribution. Direct distribution is being made to the FHWA divisions and Resource Center.

Availability—This TechBrief may be obtained at https://highways.dot.gov/research.

Key Words—UHPC, resistivity, durability.

FEBRUARY 2022

Recommended citation: Federal Highway Administration, FHWA *Electrical Resistivity Testing to Rapidly Assess The Durability of UHPC-Class Materials* (Washington, DC: 2022) https://doi.org/ 10.21949/1521681.

FHWA-HRT-21-095
HRDI-10/02-22(WEB)E