TASK REPORT

Title: Factors That Influence the Variability of Concrete Surface Resistivity of Field Cast Samples

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Final Report

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APPROXIMATE CONVERSION TO SI UNITS (FROM FHWA)

Symbol	When You Know	Multiply By	To Find	Symbol
Length				
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.924	meters	m
mi	miles	2.62	kilometers	km
Area				
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
mi^2	square miles	2.59	square kilometers	km^2
Volume				
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
NOTE: volumes greater than 2000 L shall be shown in m^3				
Mass				
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
Temperature (exact degrees)				
°F	Fahrenheit	5 (F-32)/9 or (F-32)/2.8	Celsius	°C
Illumination				
fc	foot-candles	20.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
Force and Pressure or Stress				
lbf	pound-force	4.45	newtons	N
lbf/in^2	pound-force per square inch	6.89	kilopascals	kPa

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16. Abstract

Before specifications can be developed for use of electrical resistivity in quality control programs, potential differences between field- and laboratory-made samples must be quantified. The present research was conducted to provide a better understanding of the effect of each of the factors studied in the variability observed between field-fabricated and laboratory-fabricated samples, to establish expected variations and formulate recommendations to reduce these offsets to expand resistivity testing to field-fabricated samples. The resistivity results showed that frequency used was significant for the least number of mixtures and should have only a minor effect. Temperature control was found to be significant for only a few mixtures (7% to 20%) and RCON™ (13% to 27%). Time of demolding was found to be significant for more mixtures with surface resistivity than bulk resistivity. Limewater curing in a communal tank vs. in individual buckets was found significant in 40% of the mixtures in both surface and bulk resistivity at 28 days. Moisture state during testing was found to be a significant variable. Significant differences in resistivity measurements were found between equipment used.

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EXECUTIVE SUMMARY

Background

The Florida Department of Transportation (FDOT) uses AASHTO T 358 [1] "Standard Method of Test for Surface Resistivity Indication of Concrete's Ability to Resist Chloride Ion Penetration" to qualify concrete mixtures containing highly reactive pozzolans. In this test, the concrete pore network and solution dictate the conductivity and resistivity of electricity through the specimen. The concrete pore network volume, size distribution, connectivity, and tortuosity are the target properties of concern that influence the concrete's ability to keep out undesirable ions. Other factors such as pore solution conductivity, concrete degree of saturation, aggregate conductivity, concrete temperature, or use of conductive fibers can also affect the electrical resistivity measurements that are not related to concrete ionic transport properties. The electrical connection between the concrete and the resistivity meter provided by moisture on the concrete surface can also influence the results.

Differences in resistivity readings between laboratory-fabricated samples and field-fabricated samples have been reported by several authors [1], [2], [3]. Before specifications can be developed for use of electrical resistivity in quality control programs, potential differences between field- and laboratory-made samples must be quantified.

The present research was conducted to provide a better understanding of the effect of each of the factors studied in the variability observed between field-fabricated and laboratory-fabricated samples, to establish expected variations and formulate recommendations to reduce these offsets to expand resistivity testing to field-fabricated samples.

Research Objectives

The research objective of this project was to determine the factors that influence the measurements in surface resistivity between specimens made in the field and in the laboratory (per AASHTO T 358).

Main Findings

Project findings can be summarized as follows:

- The resistivity results showed that frequency used was significant for the least number of mixtures and should have only a minor effect.
- Temperature control was found to be significant for only a few mixtures (7% to 20%) and RCON™ (13% to 27%).
- Time of demolding was found to be significant for more mixtures with surface resistivity than bulk resistivity.
- Limewater curing in a communal tank vs. in individual buckets was found significant in 40% of the mixtures in both surface and bulk resistivity at 28 days.

- Moisture state during testing was found to be a significant variable.
- Significant differences in resistivity measurements were found between equipment used.

Recommendations

Based upon the findings from this study, the following recommendations are made:

- Moisture state is not difficult to control during testing. Strict compliance with the ASTM standards should be followed to ensure reliable electrical resistivity measurements.
- Samples should be cured in buckets with new solution and should not be mixed with samples from other mixtures. Solution should also not be reused.
- Samples should be rejected if not demolded and final curing is not started within 48 hours after fabrication.
- If used as a quality control tool, concrete samples should be cured in temperature-controlled curing boxes or insulated coolers that can maintain the temperature in the range required by ASTM C31 for standard initial curing (ASTM C31 section 10.1.2.1).

Future work

The following topics should be considered for future research on concrete resistivity measurements:

- How to use concrete resistivity measurements in service life analysis
- Concrete resistivity sensor uses in the field.
- How w/cm variability in the field affects concrete resistivity measurements.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

1. INTRODUCTION

1.1. Background

The Florida Department of Transportation (FDOT) uses AASHTO T 358 [1] "Standard Method of Test for Surface Resistivity Indication of Concrete's Ability to Resist Chloride Ion Penetration" to qualify concrete mixtures containing highly reactive pozzolans. In this test, the concrete pore network and solution dictate the conductivity and resistivity of electricity through the specimen. The concrete pore network volume, size distribution, connectivity, and tortuosity are the target properties of concern that influence the concrete's ability to keep out undesirable ions. Other factors can also affect the electrical resistivity measurements that are not related to concrete ionic transport properties. Higher pore solution ionic concentrations conduct electricity more easily. Pores that are dry and do not contain pore solution will not conduct electricity, making the concrete degree of saturation a critical parameter that can influence the results. Temperature affects the concrete in two ways. High concrete temperatures, especially at early ages, accelerate the cement hydration reaction, but at the same time, result in a pore system that has higher transport properties than concrete cured at lower temperatures. The concrete electrical resistivity is a function of the temperature at the time of testing, with higher temperatures giving lower resistivity values than lower temperatures [4], [5]. The electrical connection between the concrete and the resistivity meter provided by moisture on the concrete surface can also influence the results.

Differences in resistivity readings between laboratory-fabricated samples and field-fabricated samples have been reported by several authors [1], [3]. Before specifications can be developed for use of electrical resistivity in quality control programs, potential differences between field- and laboratory-made samples must be quantified.

The present research was conducted to provide a better understanding of the effect of each of the factors studied in the variability observed between field-fabricated and laboratory fabricated-samples, to establish expected variations and formulate recommendations to reduce these offsets to expand resistivity testing to field-fabricated samples.

1.2. Research Objectives

The research objective of this project was to determine the factors that influence the measurements in surface resistivity between specimens made in the field and in the laboratory (per AASHTO T 358).

1.3. Research Approach

To accomplish the project objective, a field- and laboratory-based experimental approach was used. A literature review was first performed to identify variables that could affect the concrete resistivity measurements of samples made in the laboratory and field. Six factors identified from the literature review were used to build an experimental matrix and conduct a ruggedness study following ASTM C1067 [6] and ASTM E1169 [7]. In the ruggedness study, surface and bulk resistivity measurements were taken using equipment made by two different manufacturers.

2. LITERATURE REVIEW

2.1. Background

Concrete structures can be made to be very durable in marine and other extremely aggressive environments. The two most important concrete durability concerns in Florida are corrosion of the reinforcing steel and sulfate attack. Both of these deterioration mechanisms involve the transport of water and aggressive chloride or sulfate ions into the concrete through one or more of the following mechanisms: diffusion, absorption, permeation, electrical migration, or hydrodynamic dispersion [8]. All of these mechanisms transport the water and ions through the concrete pores that are filled or partially filled with pore solution. Once corrosion does begin, the corrosion rate I_{corr} is a function of the concrete resistivity as shown in Equation 1:

$$I_{corr} = \frac{k_0}{\rho(t)} \times F_{cl} \times F_{Galv} \times F_{O_2} \qquad \text{Equation 1}$$

Where k_0 is a regression parameter, $\rho(t)$ is the electrical resistivity at time t, F_{cl} is a factor to account for the influence of chloride content, F_{Galv} is the factor to account for the galvanic effect, and F_{O2} is a factor to account for oxygen content [9], [10]. Because the electrical conductivity of the pore solution is typically orders of magnitude higher than that of the other phases in concrete, the pore network ionic transport properties and electrical properties are related. Archie's law first empirically determined that the transport properties of porous media are proportional to their electrical resistivity [11]. A material property called the formation factor F was made that relates the concrete pore system volume φ and connectivity β to the concrete electrical resistivity ρ and pore solution resistivity ρ_0 or diffusion coefficient D and self-diffusion coefficient of chloride ions in an infinite solution D_0 in Equation 2:

$$F \equiv \frac{D_o}{D} \equiv \frac{\rho}{\rho_o} \cong \frac{1}{\phi}\frac{1}{\beta} \qquad \text{Equation 2}$$

A low concrete diffusion coefficient can be achieved in the structure through water-cementitious material ratio (w/cm) control, use of supplementary cementitious materials (SCMs), and good construction practices including curing according to best practices. When combined with sufficient concrete cover, these measures can result in a structure with a long service life. Because of its relationship with the concrete pore structure and diffusion coefficient, the concrete electrical resistivity is often used as a rapid measure of the concrete durability because of its correlation to concrete absorption and non-steady state diffusion coefficient, as shown in Figure 1 and Figure 2 [12]. It has traditionally been used to qualify concrete mixtures for durability using laboratory-made specimens. There is a desire to use electrical tests as a quality control tool for field-produced concrete cured initially in the field before being transported to the laboratory for curing and storage. A review of concrete electrical properties and the effects of concrete materials, fabrication and curing procedures, measurement conditions and methods used, and experiences using resistivity as a concrete acceptance test follows.

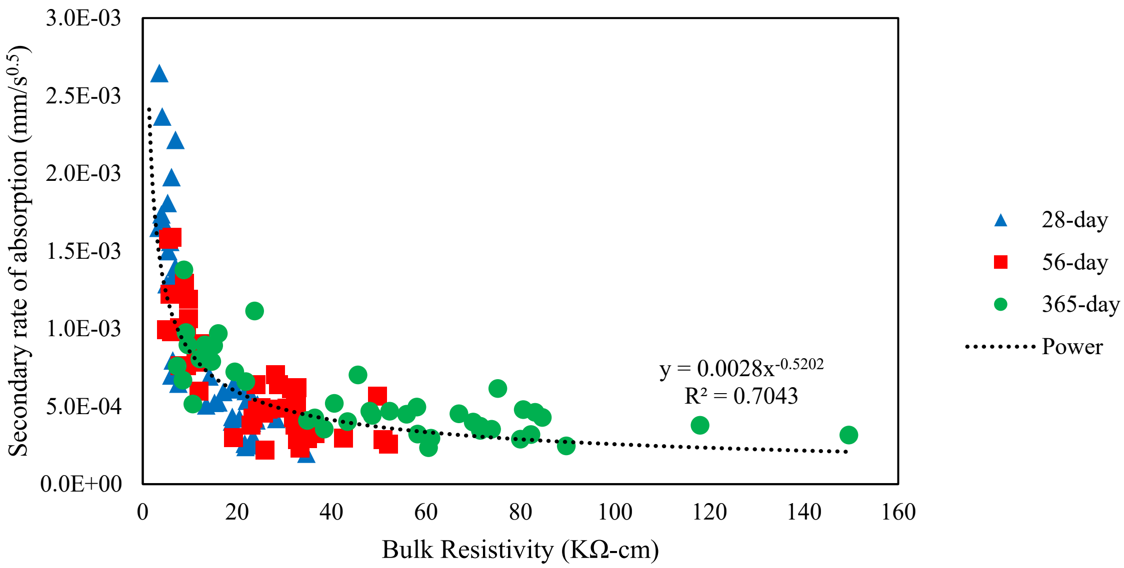

Figure 1. Relationship between concrete bulk resistivity and secondary rate of water absorption, used with permission from [12]

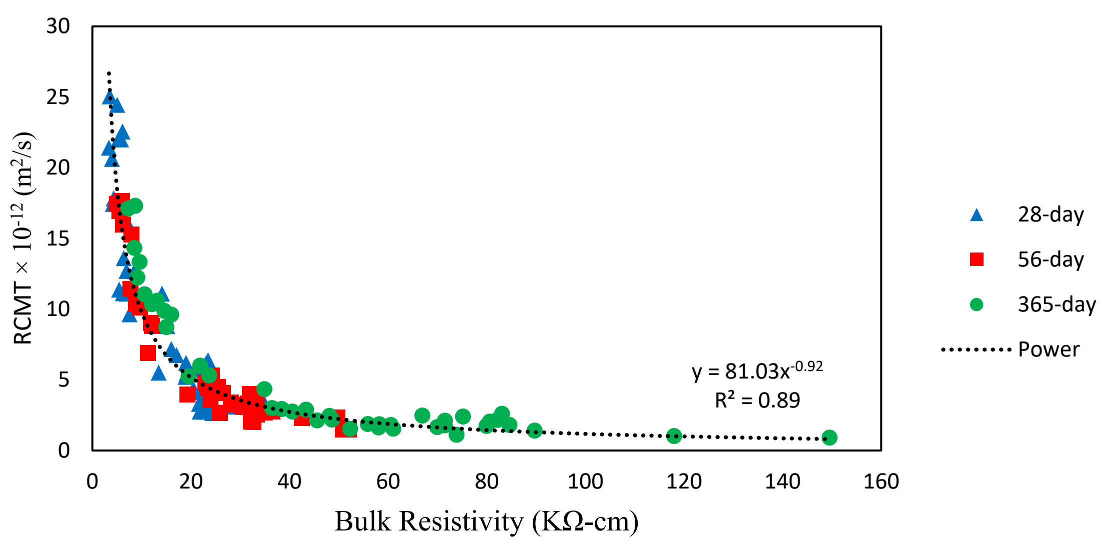

Figure 2. Relationship between bulk resistivity and non-steady state chloride diffusion coefficient, used with permission from [12]

2.2. Concrete Electrical Measurement Methods

With respect to its electrical properties, concrete acts as both a resistor and capacitor. Direct current induces polarization within the sample at interfaces including contact points for electrodes, contact the exterior of the sample, and internal interfaces between materials and material phases within the composite material. This polarization can result in erroneous measurements. The use of AC current reduces this effect, but the reactance to this capacitive effect reduces the resistance measured. This is similar in concept to how water sloshing in a tank at the top of a building acts as a damper. As a result, the resistive and capacitive effects measured using AC currents gives a measured "impedance." The capacitive effects are not related to the formation factor and need to be minimized to be able to use concrete electrical measurements for durability assessment [13]. The methods used to minimize the concrete capacitive effects can have a large effect on the measured results and implied concrete durability.

2.2.1. Measurement Frequency

AC measurements are used to minimize the effects of concrete capacitance on the resistivity measured. Both sine and square AC waves have been used in the past to measure concrete resistivity [14], [15], [16] and have used frequencies ranging from 0.1 Hz to 100 kHz [16]. The Standard Test Method for Surface Resistivity Indication of Concrete's Ability to Resist Chloride Ion Penetration (AASHTO T 358) requires that a frequency between 10 and 1000 Hz be used to measure surface resistivity of concrete specimens. The true concrete resistivity occurs when the phase angle of the impedance is zero, or the reactance component of the measured impedance is zero. As this is not practical to measure, the frequency used should be selected to reduce this response. The reactance is more affected by the concrete microstructure at high frequencies, and the electrode-concrete interface at low frequencies. Frequencies below 500 Hz generally affect uniaxial (bulk) resistivity measurements more than surface resistivity measurements because the instrument-concrete interface is more sensitive in the uniaxial (bulk) resistivity than surface resistivity configuration [13], [17], [18]. Use of internal embedded electrodes reduces this effect compared to external electrodes because of the better contact [17]. A comparison of the bulk resistivity measured using three commercially available resistivity meters on concrete made with OPC, 25% slag cement, and 50% slag cement at 3, 7, 14, 28, and 56 days showed a difference in bulk resistivity measurements of 2.3% difference. The three meters used frequencies of 40 Hz, 350 Hz, and 1000 Hz. This variation is at least partially a result of the difference in frequency used [19], however the results are within the expected within-laboratory coefficient of variation [20]. A comparison of the CNS Farnell resistivity meter that uses a frequency of 13 Hz and the Proceq Resipod that uses a frequency of 40 Hz at two laboratories showed that the results are statistically equivalent [21].

2.2.2. Sample Geometry

Concrete electrical resistivity is a material property independent of concrete sample size, shape, or other parameters. The geometry used to measure the concrete electrical resistivity can greatly affect the impedance value measured. This geometry effect can be accounted for analytically for some electrode arrangements and sample types to calculate the concrete resistivity. Concrete resistivity is calculated using Equation 3:

$$\rho = Rk \qquad \text{Equation 3}$$

Where R is the concrete resistance, and k is the geometry correction factor. The geometry correction factor is dependent on the sample and measurement geometry used.

The most popular concrete resistivity arrangement uses a four-point Wenner probe. Four-point Wenner probes have been used to measure the concrete resistivity using contact points on the same surface, hence the name surface resistivity. The current is applied using the outer two points, while the voltage is measured using the two inner points [22], as shown in Figure 3. The geometry correction factor for a four-point Wenner probe is shown in Equation 4 [4]:

$$k = \frac{2\pi a}{1.09 - \frac{0.527}{\frac{d}{a}} + \frac{7.34}{\left(\frac{d}{a}\right)^2}} \qquad \text{Equation 4}$$

Where *d* is the cylinder diameter. This equation assumes an infinite cylindrical sample. In order to ensure that the sample geometry will meet this assumption, the cylinder diameter must be less than 4 times the electrode spacing, and that the cylinder length is at least 5 times the electrode spacing [4], [22].

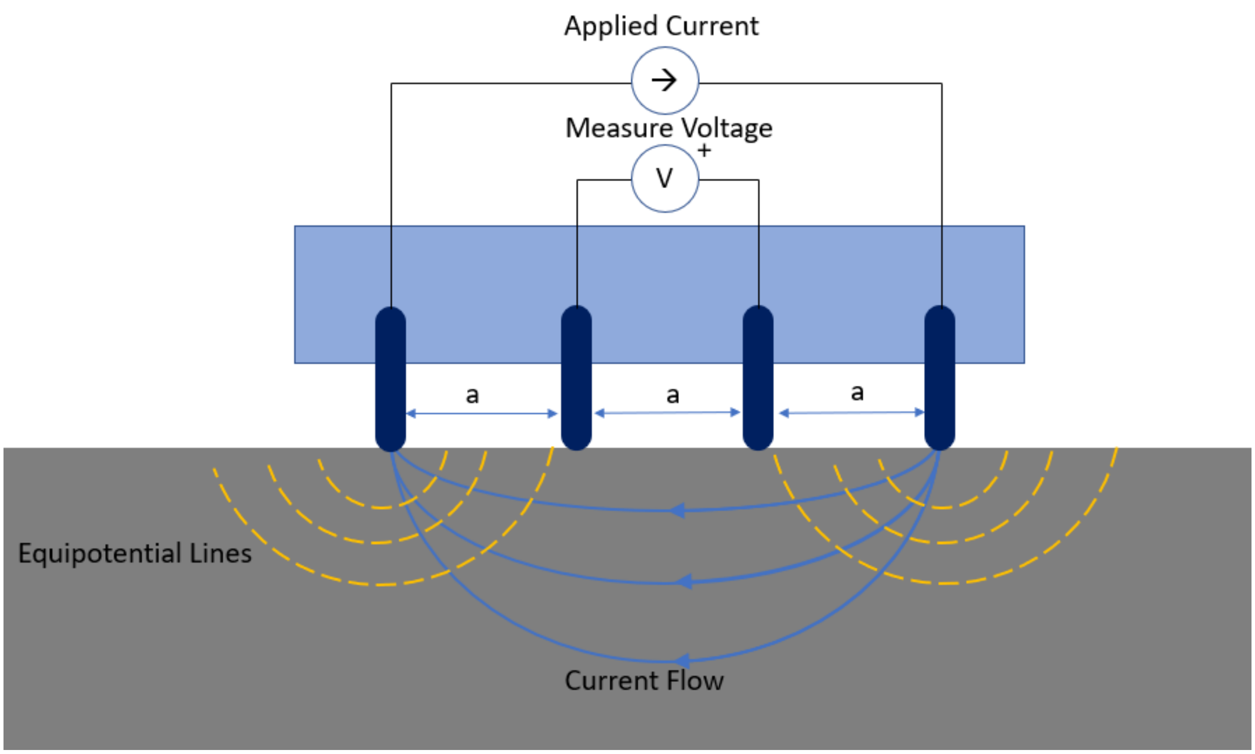

Figure 3. Four-Point Wenner Probe Measurement System, after [23]

Two-point resistivity tests, also known as uniaxial or bulk resistivity tests, use two electrodes placed within the concrete or external to the concrete. The most common method used is to place two typically metal conductive plates on the ends of a concrete cylinder. A conductive medium like a wet sponge [13], conductive jelly [20], or other conductive material is placed between the plates to ensure good conduction between the plates and sample and reduce contact interference. An AC current is applied to the plates, with the drop in electrical potential measured between the two plates [13]. The electrical resistance of the sponges is measured with the concrete and subtracted from the measured resistance using Equation 5 [24]:

$$R_{cylinder} = R_{measured} - R_{top\ sponge} - R_{bottom\ sponge} \qquad \text{Equation 5}$$

The geometry correction factor used for uniaxial resistance is shown in Equation 6 [13]:

$$k = \frac{A}{L} \qquad \text{Equation 6}$$

Where A is the concrete cross-sectional area perpendicular to the direction of current flow, and L is the concrete cylinder height or concrete length between the plates.

2.2.3. Concrete Pore Solution

For most concrete materials, the concrete pore solution is orders of magnitude more conductive than the solid material such as aggregates, cement particles, or solid hydration product. Consequently, the measurement obtained by concrete electrical resistivity is typically dominated by the concrete pore structure and pore solution conductivity. The measured concrete resistivity can be normalized by the pore solution resistivity to calculate the formation factor, as shown in Equation 2. The concrete pore solution resistivity is predominantly a function of the pore solution alkali content [25]. The pore solution alkali resistivity can be estimated using the cementitious material composition, degree of hydration, and assumed value for alkali binding [12], [25]. It can also be measured using sensors embedded in the concrete [26] or from pore solution extracted from the concrete [12], [26]. Concrete constituent materials that affect the pore solution composition and resistivity are discussed in section 2.3.

2.2.4. Electrical Property Test Methods

Standard test methods have existed for several decades to measure the concrete electrical properties as indices for permeability and durability. While each test is based on the same physical concept that the permeability and electrical properties are both a function of the pore structure, they have different requirements that affect the measurements and interpretation of results and are worth reviewing.

2.2.4.1. ASTM C1202

ASTM C1202 "Standard Test Method for Electrical Indication of Concrete's Ability to Resist Chloride Ion Penetration" [27] was developed to provide an index of the concrete chloride permeability based on correlations found between charge measured passing through concrete under standard conditions and chloride penetration measured in long-term chloride ponding tests conducted according to AASHTO T 259 [28], [29]. It was recognized that changes in concrete pore solution or other concrete constituent materials could affect this relationship. Consequently, this test method is only applicable to concrete where the correlation between ASTM C1202 and AASHTO T 259 has been developed. Samples used can be cured in a fog room or limewater tank for 28 or 56 days. Alternatively, the samples can be cured using an accelerated method in which the sample is cured in a moist room or limewater tank meeting ASTM C511 after demolding until an age of 7 days, followed by curing in limewater at 100.4°F ± 3.6°F for 21 days. In this test method, a 2-in.-thick, 4-in.-diameter concrete sample is first vacuum saturated. The sample is vacuum saturated to achieve consistent saturation between samples, including cored samples, because differences in concrete saturation will greatly affect the measured results. In this test, the concrete sample is vacuum saturated by placing the sample in a vacuum desiccator at less than 2 in. (50 mm) mercury for 3 hrs, after which water is allowed to fill the desiccator while under vacuum. The concrete remains under water in the vacuum for 1 hr. the vacuum is then released. After soaking the sample in the water for 18 ± 2 hrs, the concrete sample is placed in a cell with 0.3 M sodium hydroxide on one side and 3 M sodium chloride on the other side, as shown in Figure 4. 60.0 ± 0.1 V DC is applied to the sample for 6 hrs. The total charge passed through the sample during the 6 hrs. is measured and recorded. The concrete permeability can be qualitatively rated for chloride ion penetrability based on the charge passed[27] , as shown in Table 1.

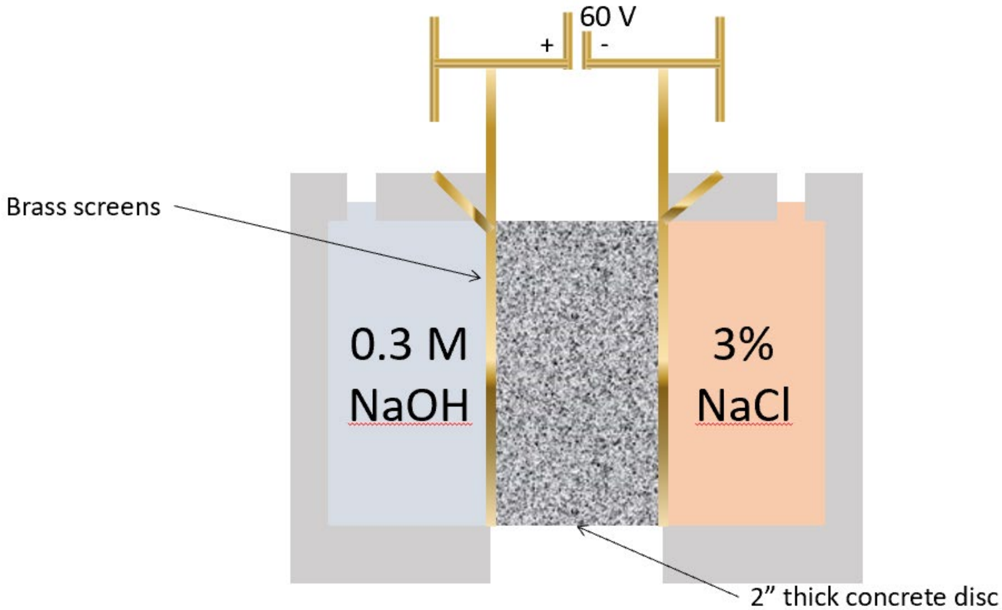

Figure 4. ASTM C1202 sample setup, after [27]

Table 1. Concrete chloride ion penetrability categories based on ASTM C1202 charge passed [27]

Charge Passed (Coulombs)	Chloride Ion Penetrability Category
< 4,000	High
2,000 – 4,000	Moderate
1,000 – 2,000	Low
100 – 1,000	Very Low
< 100	Negligible

ASTM C1202 has several drawbacks that have led to criticism and development of newer test methods to measure concrete electrical properties:

- The test takes over 24 hours to perform and is labor intensive. The 6 hr electrical potential application is unnecessary – a much shorter time period can be used to obtain the concrete electrical properties [30].
- This test method is affected by concrete constituent materials that can alter the pore solution composition but not the pore structure. Vacuum saturation fills the concrete pores, including air voids. Water-filled air voids will conduct electricity, but are often not filled in the field and do not contribute to chloride transport when empty [31].
- Differences in concrete pore solution from chemical admixtures or conductive fibers can increase the charge passed, even though these materials may not affect the concrete pore system [27]
- 60 V can induce a high electrical current in the concrete, especially in moderate or high permeability concrete. The charge passed is a function of the concrete temperature during testing, with higher temperatures leading to higher charge passed [30].
- Concrete sample thickness variation within the tolerances of ± ¼ in. permitted by the standard can result in a difference of measured charge passed of 12% [27], [30] [27]
- The test has a high coefficient of variation of 12.3% for single operators, and a multilaboratory difference of 18% [27].

2.2.4.2. ASTM C1760

ASTM C1760 Standard Test Method for Bulk Electrical Conductivity of Hardened Concrete [32] provides a method to measure the concrete electrical properties in a two-point configuration. This method was withdrawn in 2021 because of the introduction of ASTM C1876 Standard test Method for Bulk Electrical Resistivity or Bulk Conductivity of Concrete [33]. ASTM C1760 is similar to ASTM C1202, with a few modifications. A 4 × 8 in. concrete cylinder or other size sample can be used without cutting. The length is measured and included in the calculations for bulk electrical conductivity. Samples are cured and conditioned in the same manner prescribed in ASTM C1202. After the sample is vacuum saturated, the same cells used in ASTM C1202 and shown in Figure 4 are attached to the sample ends. A 60.0 ± 0.1 V DC potential is applied to the concrete; however, the current is only measured at 60 ± 5 s after application. The delay in measuring the sample is used to allow the sample current to stabilize because of capacitance effects. The concrete bulk electrical conductivity σ is then calculated using Equation 7:

$$\sigma = \frac{I_1}{V}\frac{4L}{\pi D^2} \qquad \text{Equation 7}$$

Where I_1 is the current measure at 1 minute, V is the applied electrical potential, L is the sample length, and D is the sample diameter. This test method has a few advantages over the ASTM C1202 test. Because the electrical potential is only applied to the concrete for a minute, the sample does not heat up to increase the charge passed. The allowance for a longer sample eliminates the need to cut the sample, saving preparation time. There are still a few drawbacks to this test method. The sample uses DC current instead of AC current, giving potential differences with other AC tests because of capacitance issues such as electrode polarization [34]. Differences in results could be expected depending on the curing method chosen [19]. The vacuum saturation used in this test should fill air voids with water, making them conductive when they would not be expected to be filled with water in the field nor be involved in ion transport [31]. Curing the samples in a moist room will cause alkalis to leach out of the concrete, artificially increasing the concrete resistivity [12], [35]. This test method was withdrawn in 2021 because ASTM C1876 can also be used to measure the concrete electrical conductivity, is easier to run, and attempts to solve some of the issues seen in this test method.

2.2.4.3. AASHTO TP 119

AASHTO TP 119 "the Standard Method of Test for Electrical Resistivity of a Concrete Cylinder Tested in a Uniaxial Resistance Test" [24] uses a two-point method to measure the concrete resistivity. In this method, a 4 × 8 in. or 6 × 12 in. concrete cylinder or core or cylinder is used to measure the concrete resistivity. Samples are cured/ conditioned by immersing the specimen in a simulated pore solution at 73 ± 4 ºF immediately after demolding for laboratory-made specimens or for a minimum of 6 days for field-made cylinders or cores. The simulated pore solution is intended to minimize alkali leaching out of the sample. The simulated pore solution used contains 0.19 M NaOH, 0.19 M KOH, and is saturated with lime. A second allowable conditioning method requires the use of 4 × 8 in. cylinders which are kept at 73 ± 4 ºF and sealed during casting until the time of testing. After the specimen conditioning is complete and they obtain the desired age, the uniaxial resistivity is measured by placing metal plates weighing of at least 1.39 lb (630 g) on each end of the specimen. A compressible medium, typically a sponge, with a maximum thickness of 8 mm is placed between the specimen and each metal plate on the end. Wires are used to connect the plates to the resistivity meter to apply the current and measure the potential drop across the specimen [24], as shown in Figure 5. The specimen concrete materials, curing method and history, diameter, length, and temperature at the time of testing are reported along with the measured resistivity [24]. The reported single-operator coefficient of variation for this test is 4.4%, while the multi-laboratory coefficient of variation is 13.2% [24].

Figure 5. Concrete sample uniaxial resistivity measured according to AASHTO TP 119, figure by Raid Alrashidi used with permission

This method addressed some of the criticisms given for ASTM C1760. It uses AC instead of DC to measure the concrete resistivity. This test method uses simpler equipment than ASTM C1760 and is easier and quicker to perform. It cures the samples in a simulated pore solution, reducing leaching. This test method has potential concerns as well. The test method uses a single simulated pore solution composition for all concrete mixtures tested regardless of the materials used. Because the pore solution composition will be different for different concrete constituent materials, a concentration gradient typically exists between the simulated pore solution and concrete pore solution [12]. This can cause alkalis or other ions to leach out of the concrete if the concrete pore solution concentration is higher than that of the simulated pore solution and increasing the measured concrete resistivity, albeit at a lower rate and extent than would likely occur in a moist room or limewater. The reverse can happen if the simulated pore solution has a higher concentration than the concrete pore solution, causing alkalis to diffuse into the concrete, reducing the concrete electrical resistivity measured. There is some concern amongst agencies that implementation of this may be difficult because of the cost of the solution and difficulty in making the solution. The test method does not require the simulated pore solution to be made new for each set of samples, nor does it require that the pore solution resistivity be measured between samples. This could lead to differences in results if the solution is reused.

2.2.4.4. ASTM C1876

ASTM C1876 "Standard Test Method for Bulk Electrical Resistivity or Bulk Conductivity of Concrete" [33] was developed to provide a simpler test method to measure concrete electrical properties and fix some of the shortcomings identified with ASTM C1760. This uniaxial resistivity test is similar to AASHTO TP 119. The test method specifies that a verification cylinder be used to verify the resistivity meter calibration. The 4 × 8 in. hollow verification cylinder must be non-conductive and contain five precision resistors with resistances distributed between about 10 Ω and 100 kΩ and connected in parallel to the two stainless steel end plates. The cylinder must have a switch to isolate one resistor at a time to measure the meter resistivity. The specification requires that the metal end plates used to measure the concrete resistivity are between 6- and 8-mm thick be used. Sponges soaked in an electrically conductive solution such as saturated limewater are placed between the metal plates and concrete ends, like in AASHTO TP 119, except that sponge thickness requirements are not given. ASTM C1876 requires that the samples be soaked in a bucket containing a simulated pore solution with 0.19 M NaOH, 0.19 M KOH, and saturated with lime at 73±4 ºF for at least 6 days prior to measuring the concrete resistivity. The resistivity must be measured after blotting off free water on the concrete cylinder surface and within five minutes of removing the concrete from the simulated pore solution. The concrete resistivity is measured using an AC current and frequency of 1-kHz by default. This test has a reported single-operator coefficient of variation of 4.3% and multi-laboratory coefficient of variation of 13.2% [33]. This test method is very similar to AASHTO TP 119 but does not provide multiple conditioning alternatives. This can help remove some confusion and differences in reported results that may arise when AASHTO TP 119 is used with different curing methods but comes with the same advantages and disadvantages described in section 2.2.4.3. Use of a 1 kHz frequency to measure the concrete resistivity should slightly improve repeatability; however, it disallows the use of several commercially available concrete resistivity meters [19].

2.2.4.5. AASHTO T 358

AASHTO T 358 "Standard Method of Test for Surface Resistivity Indication of Concrete's Ability to Resist Chloride Ion Penetration" [36] uses a four-point Wenner probe arrangement to measure the surface resistivity of concrete. In this method, the surface resistivity of at least three concrete cylinders, 4 × 8 in., or 6 × 12 in. cast concrete specimens are measured. After initial curing in the mold, the specimens are marked at 4 equidistant circumferential points on the top that extend down the concrete sides to mark locations to measure the concrete resistivity at four locations. After marking the specimen, they are cured in either limewater tanks, a moist-curing room, or using the accelerated curing method described in ASTM C1202. After removing the samples from curing, they are wiped with a wet towel or sponge to remove free surface water on the specimens. Each sample is placed in a holder horizontally to keep it from rolling away during measurement, as shown in Figure 6. The probe is placed on the sample surface along the first line at 0 degrees to measure the concrete surface resistivity. After measurement, the sample is rotated, after which the resistivity meter is placed on the concrete on the line 90 degrees to the first line used to measure the concrete surface resistivity. The specimens are rotated and measured until the specimen surface resistivity has been measured on each of the four lines twice. The concrete temperature during measurements should be recorded [36]. This test method was found to have a within-lab repeatability COV of 4.28% and between-lab reproducibility COV of 8.52% for samples made from 12 different concrete mixtures tested at 14 laboratories [21]. This test method has had many years of good use. There is a concern that curing solution could remain on the surface and provide a short-circuit for the electricity during the test. The opposite problem of surface drying could occur and result in artificially and erroneously inflated resistivity results.

Figure 6. Concrete sample surface resistivity measured according to AASHTO T 358, figure by Raid Alrashidi used with permission

2.3. Concrete Properties that Influence Transport Properties and Electrical Measurements

Concrete electrical measurements are used to inform about the concrete pore system and transport properties. Some material properties will influence the concrete transport properties and consequently the electrical measurements. Concrete materials, mixture proportions, and curing methods used will affect the concrete transport properties and in turn the concrete electrical properties measured, however they do not always affect each equally. Control of these variables will help ensure that concrete quality can be measured reliably with high repeatability.

2.3.1. Materials and Mixture Proportions

2.3.1.1. W/CM

Concrete water-cementitious material ratio (w/cm) has been known for over 100 years to be the primary factor in controlling the concrete strength and transport properties [37]. Concrete pores are water or vapor filled space. The water-filled space during mixing can be replaced with solid hydration products during hydration. The portland cement and water react together to form hydration products such as calcium-silicate-hydrate (C-S-H) that have a lower density than that of the portland cement. This enables the hydration products to take up more room as solid material than the cement took up before hydration, filling in some of the space previously filled in with water. The lower the concrete w/cm, the fewer hydration products required to fill in the space initially occupied by mixing water to achieve a low porosity [38]. Concrete water control and reduction can help reduce the concrete porosity, transport properties, and consequently increase the concrete resistivity. A low w/cm will also increase the ionic concentration in the pore solution, reducing the measured concrete resistivity while not necessarily affecting the pore structure. Overall, the reduction in pore solution resistivity, and reduction in pore system volume and connectivity from using a lower w/cm results in an overall increase in the concrete resistivity. For example, in one recent FDOT-sponsored study a decrease in the w/cm from 0.44 to 0.35 for samples from an ordinary portland cement concrete mixture cured in the moist room resulted in a decrease in the measured pore solution resistivity from 16.9 to 12.2 Ω-cm and an increase in the measured concrete bulk resistivity at 28 days from 4.3 to 8.5 kΩ-cm [12]. Figure 7 shows a comparison of the pore solution resistivity measured for the same cementitious material combinations at 0.35 and 0.44 w/cm [12].

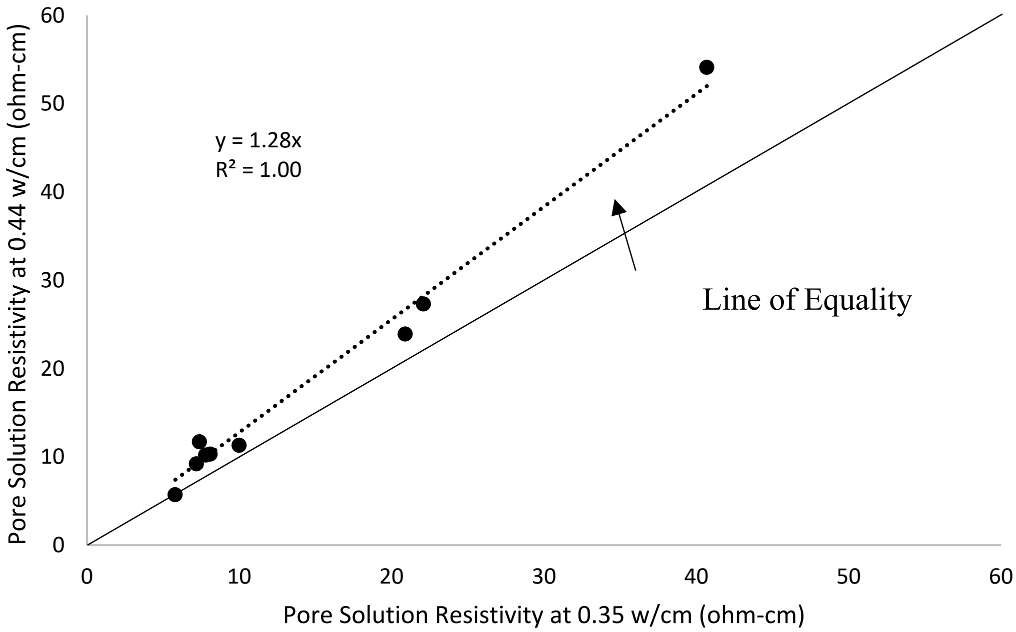

Figure 7. Pore solution resistivity for the same cementitious material combinations at 0.35 and 0.44 w/cm [12]

2.3.1.2. Cement

Portland cement composition can have a large impact on the measured resistivity value, mainly by affecting the pore system and by supplying alkalis to the pore solution that substantially determine the pore solution resistivity. Cement composition and fineness will affect the pore system refinement and development by producing different hydration products. Cement fineness will principally affect the rate of porosity refinement at early ages [39]. Limestone fines in the cement will produce hemicarboaluminate and monocarboaluminate phases and stabilize ettringite formation [40]. This will impart a slight increase in strength and reduction in porosity when small amounts typically under 8% are used [41], and approximately equal strength to a system without limestone fines when fifteen limestone percent fines are used [42], [43]. Alkalis released into the pore solution from the cement are a function of the cement total alkali content, cement degree of hydration, and alkali binding by the cement hydration products. The National Institute of Standards and Technology (NIST) created an online calculator to estimate the concrete pore solution alkali content and resistivity for a given ASTM C150 cement composition based on an assumed cement degree of hydration and alkali binding factor [44]. The pore solution conductivity can be calculated within 8% using their simple model that only includes the OH-, Na+, and K+ concentrations. This shows that the other ions in solution are only minor contributors to the pore solution conductivity, with sulfate ions typically contributing to less than 2% of the pore solution conductivity [25]. Additional empirical models have been created to estimate the pore solution alkali composition [45].

2.3.1.3. SCMs

SCMs affect the concrete resistivity by altering the pore system and altering the pore solution composition and resistivity. SCMs promote pore system refinement by the filler effect and by producing hydration products that reduce connectivity [46]. Improved particle packing from the use of very fine SCMs such as silica fume or ultra-fine fly ash can fill in space, especially in the interfacial transition zone (ITZ) between the aggregate and cement paste [38]. This has the effect of reducing the concrete transport properties and increasing the concrete resistivity at the same time.

SCMs can alter the concrete resistivity by binding alkalis that influence the pore solution resistivity, or in other cases releasing alkalis from the SCM into the pore solution. The hydroxyl concentration is closely tied to the pore solution resistivity and is primarily a function of the sodium and potassium concentration [25]. The pore solution hydroxyl concentration was found empirically to be a function of the constituent material alkali content, calcium content, and silica content, as shown in Equation 8 [45]:

$$OH^- = 6.03\frac{Na_2O_e \times CaO}{(SiO_2)^2} \qquad \text{Equation 8}$$

Where OH^- is the hydroxyl concentration, Na_2O_e is the sodium equivalent alkali concentration in the composite cementitious system, CaO is the calcium oxide concentration in the composite cementitious system, and SiO_2 is the silicon dioxide concentration in the composite cementitious system. The relationship shown in Equation 8 was based on mixtures all at 0.5 w/cm and with 100% portland cement with alkali contents ranging from 0.36 to 1.09%, 25 to 70% fly ash binary mixtures with CaO contents ranging from 1.1 to 30.0% and Na_2O_e contents ranging from 1.4 to 9.7%, binary mixtures with 25 to 50% slag cement, binary mixtures with 5 to 10% silica fume, binary mixtures with 10 to 20% metakaolin, and ternary mixtures with silica fume with either fly ash or slag cement [45]. A recent study sponsored by FDOT made adjustments to the equation to account for additional data at different w/cm in Equation 9 [12], and found empirically an equation to calculate the pore solution resistivity in Equation 10 [12]:

$$OH^- = \frac{3.015}{\frac{w}{cm}}\frac{Na_2O_e \times CaO}{(SiO_2)^2} \qquad \text{Equation 9}$$

$$\rho = \frac{1.325\left(\frac{w}{cm}\right)(SiO_2)^2}{(Na_2O_e \times CaO)} \qquad \text{Equation 10}$$

2.3.1.4. Aggregate

Aggregate content is a significant parameter in determining the concrete resistivity. Overall, the relationship between concrete resistivity and paste resistivity for two cementitious systems was found to follow a power-law relationship with the paste content as shown in Equation 11 [47].

$$\rho_c = \rho_p(1 - V_a)^{-1.5606} \qquad \text{Equation 11}$$

Where ρ_c is the concrete resistivity, ρ_p is the paste resistivity, and V_a is the aggregate volume.

Equation 11 assumes that the aggregate conductivity is negligible. Coarse aggregate content has been found in one study to affect the concrete resistivity according to the simple rule of mixtures, implying that the concrete resistivity is linearly related to the aggregate content [48]. Aggregate size has been shown to have very little impact on the concrete resistivity [48]. This shows that the changes to the ITZ by changes to aggregate size have only a minor effect at most on the pore structure connectivity and that it is the paste volume that really controls the pore system and resistivity [48]. While the aggregate size does not result in differences in concrete resistivity, it was found that one will get higher variability in surface resistivity results with larger maximum aggregate size, likely because larger aggregates can affect the electrical current locally [22]. This effect may be less in uniaxial resistivity tests because the electrical current flows through the entire cross-section.

The relationship found between concrete electrical properties and ionic transport properties relies on the cementitious pore system contributions being dominant with the aggregate contributions negligible. This works for most portland cement concrete because the electrical resistivity of aggregates is typically orders of magnitude higher than that of the cement paste. For example, granite has an electrical resistivity between 5×10^6 and 5000×10^6 kΩ-cm. The electrical resistivity of limestone is typically between 400 and 5000 kΩ-cm [49]. Because of the high resistivity of typical aggregates used, for a given paste system and volume, aggregates most commonly used in transportation infrastructure do not affect the electrical resistivity unless the paste system resistivity is high from use of a low w/cm or a particularly high porosity aggregate [49]. Some less commonly used aggregates that are metallic, such as magnetite or hematite, that can have electrical resistivity values closer to that of cement paste can reduce the concrete resistivity [3]. Use of conductive aggregates makes use of electrical resistivity measurements difficult for concrete quality control unless corrections for the aggregate properties are made. Similar to other aggregates, the contribution of lightweight aggregates to concrete electrical resistivity depends on the aggregate porosity. Concrete made with different lightweight aggregates has been shown to give similar 28-day resistivity values as a control concrete that increased at 56 days as the lightweight aggregate was able to add internal curing and provide some pozzolanic reaction at the surface with the cement paste [50].

2.3.1.5. Chemical admixtures

Chemical admixtures can affect the concrete resistivity by altering cement hydration to change the pore system and by altering the pore solution ionic composition and concentration. Some admixtures like accelerators and retarders can affect the concrete hydration, especially at early ages. This would have a corresponding effect on the concrete porosity and consequently concrete resistivity. Corrosion-inhibiting admixtures that contain calcium nitrite can reduce the concrete resistivity by as much as a third by increasing the pore solution ionic concentration [51]. Caution should be exercised when interpreting the resistivity results of concrete containing corrosion-inhibitors or other admixtures with high ionic concentrations.

2.3.1.6. Air content

Entrained air affects the concrete resistivity much the same as any empty or partially saturated pore would. Electricity only conducts through the solution and not through any vapor present in the void. Entrained air void systems are designed to not be saturated under normal circumstances so that when a freezing event occurs, they have plenty of space available for ice crystals to form without causing pressures on the pore walls and microcracking. If the air void becomes saturated because the concrete is submerged in water for a lengthy period of time or the concrete is vacuum saturated or exposed to water under pressure, the effect is an increase in the degree of concrete saturation and its subsequent reduction in resistivity [31]. The concrete formation factor is independent of the air content for concrete at the transition between initial and secondary water absorption, also known as the knick-point [31]. At this point, water has filled the capillary and gel pores, but not the air voids [31], [52].

2.3.1.7. Fibers

Any solid conductive material in the concrete will conduct electricity and lower the measured resistivity, even if it does not change the concrete transport properties. Embedded reinforcing steel or conductive fibers such as steel or carbon fibers are conductive and will alter the concrete resistivity. This is well known, and it is advised in ASTM C1202 to not use that particular test with these materials [27]. Other conductive materials that have been used in concrete before are graphene [53] and agricultural residue ash with high carbon content [54].

2.3.2. Sample Curing

2.3.2.1. Temperature

Curing portland cement concrete at high temperatures is known to affect the concrete microstructural development. While high temperatures accelerate the cement chemical reactions, they do so at the cost of forming hydration products that are denser and take up less space in the microstructure, leaving more space as porosity [55]. Calcium-silicate-hydrate (C-S-H), the cement hydration phase that imparts most of the strength to portland cement concrete, incorporates less water in its structure and becomes denser [55]. High temperatures also cause some hydration products to become unstable, leading to different hydration product formation. For example, ettringite becomes unstable at temperatures above about 158°F, or in some cases even lower temperatures [56]. Because strength is principally related to the capillary porosity present in the concrete, an increase in the porosity results in reduced strength and resistivity. This increase in early-age strength from the higher degree of hydration at high temperatures and consequent reduced later-age strength compared to concrete cured at lower temperatures is termed the cross-over effect. It is so named because the lower early-age strength of concrete cured at lower temperatures crosses over the strength curve of concrete cured at higher temperatures to show higher strength [57], as shown schematically in Figure 8.

Illustration showing the cross-over effect for concrete cured at different temperatures

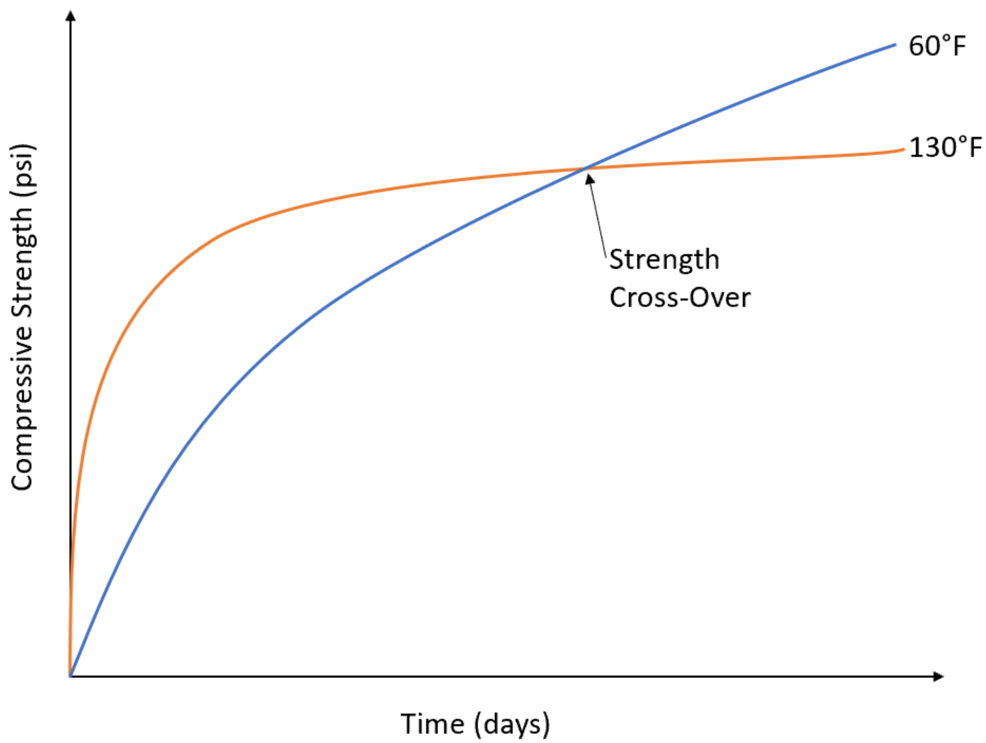

Figure 8. Illustration showing the cross-over effect for concrete cured at different temperatures

The cross-over effect does not necessarily impact all mixtures equally and does not result in the strength cross over at the same point in time. A concrete mixture with 20% Class F fly ash was seen to have a 28-day resistivity value 25% higher when cured in 76°F limewater compared to 70°F. The 28-day resistivity value of the mixture made without SCMs and cured at 76°F was shown to be statistically the same as that cured at 70°F [2].

An example of the long-term strength reduction seen with elevated temperature curing was recently described for concrete containing limestone fines and calcined clay. This blend of portland cement, limestone, and calcined clay, called LC3, has excellent strength development at room temperature because the carbon dioxide from the limestone and alumina from the calcined clay allow for the formation of hemicarboaluminate and monocarboaluminate. This allows the sulfate in the cement to be used to form more ettringite in lieu of calcium monosulfoaluminate. This ettringite stabilization provides higher strength. At 122°F (50°C) compared to 80.6°F (27°C) in these blends, more alumina is taken up into the calcium-alumino-silicate-hydrates (C-A-S-H). This results in a significant decrease in the ettringite and carbo-aluminate phases. The higher temperature in this system also reduces the cement degree of hydration at 28 days. The net result is a significant increase in porosity and decrease of over 1/3 of the compressive strength at 28 days for the samples cured at 122°F (50°C) compared to at 80.6°F (27°C) [58]. A strength decrease and increase in porosity from elevated temperatures would translate to a significant decrease in resistivity.

2.3.2.2. Relative Humidity

Concrete degree of saturation affects the concrete resistivity to a large part because pores can only transmit electrical currents through pore solution [59]. Partially saturated pores can also cause discontinuities in the pore network, increasing the electrical resistivity [60]. When the concrete dries, the pore solution concentration will increase, decreasing the pore solution resistivity [59]. The concrete degree of saturation is typically measured using the weight difference between the sample under test conditions and oven dry conditions divided by the mass loss between fully saturated and oven dry conditions [60].

The concrete resistivity can be described neglecting the change in pore solution concentration with drying in Equation 12 and an approximation for the effect of saturation degree on pore solution resistivity in Equation 13 [60], [61]:

$$\rho_c = \left(\rho_p^0\right)(F)\left(\frac{1}{f(S)}\right) \qquad \text{Equation 12}$$

$$f(S) = S^m \qquad \text{Equation 13}$$

Where S is the concrete degree of saturation ranging from 0 at dry conditions to 1 for fully saturated, ρ^0_p is the paste resistivity at saturation, F is the concrete formation factor, $f(S)$ is the saturation factor, and m is a saturation coefficient typically between 3.0 and 5.0 for cementitious materials [60], [61]. The first term in Equation 12 represents the pore solution resistivity, the second term accounts for the total pore volume present in the system, while the third term accounts for the degree of saturation on the pore connectivity [60]. The assumptions used in the analysis in Equation 12 and Equation 13, as well as the variation in m has made it difficult in practice to implement use of sealed concrete samples for concrete quality control testing. Vacuum saturation has been used as a strategy to reduce the variability from concrete moisture state on electrical test results. Vacuum saturation is specified for use in ASTM C1202 for this reason. Vacuum saturation of sealed samples has been proposed as a method to prevent leaching while eliminating uncertainty associated with concrete partial saturation. While vacuum saturation has some appeal from a variability point of view, it will fill entrained air voids and overestimate the concrete transport properties [31]. The concrete hydration can also stop in sealed samples in concrete made with low w/cm, reducing the potential resistivity measured, even if later vacuum saturated right before testing [60].

2.3.2.3. Leaching

Concrete cured under any condition except sealed curing will invariably involve moisture and ion transport to and/or from the concrete. Concrete samples for resistivity testing have been suggested to be cured using an ASTM C511 [62] compliant moist room, limewater tank, sealed curing, curing in a simulated pore solution, or limewater at room temperature for 7 days followed by limewater at 100°F for 21 days to accelerate the resistivity gain [24], [36]. Curing in a simulated pore solution is intended to reduce the alkali concentration gradient between the concrete pore solution and the curing solution, reducing leaching out of the concrete. In order for this to happen, the simulated pore solution alkali concentrations should match that of the concrete pore solution. Any difference in pore solution concentration could result in alkali leaching or migration into the sample, causing unexpected changes in the measured resistivity and error in calculating the formation factor [12]. AASHTO TP 119 standardized the simulated pore solution to reduce the complexity of predicting the pore solution composition and then fabricating it [24]. This could result in variability in measured results.

Moist room curing can leach out significant amounts of alkalis from the concrete. A comparison of resistivity measurements of specimens cured in a moist room or in simulated pore solution shown in Figure 9 clearly shows the increase in resistivity from leaching [12]. In moist rooms, water that has a low alkali concentration can drip onto the sample and leach out alkalis [35]. There is a concern that the amount to of alkalis leached could depend on the sample location in the fog room, including whether it is on a shelf under other samples where the dripping water may have a higher alkali concentration from contact with the samples above. Moist room cured samples are assumed in AASHTO T 358 to give resistivity values 10% higher than limewater cured samples [36]. How much different the limewater sample resistivity values are than moist room cured samples will depend however on the alkali concentration of the limewater and when the limewater was changed and refreshed. Caution should be exercised when using acceptance thresholds that the curing method used matches that assumed for the acceptance threshold.

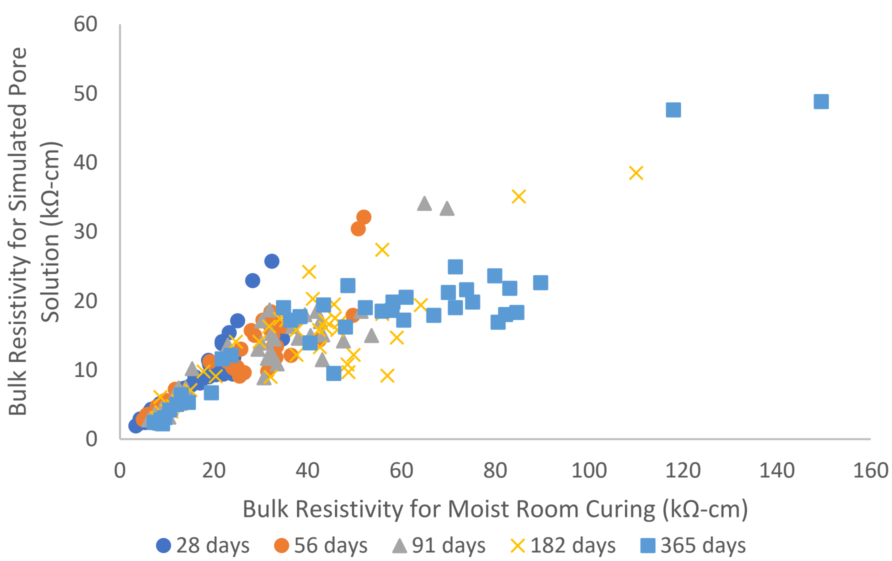

Figure 9. Comparison of concrete bulk resistivity measurements for samples cured in moist room or simulated pore solution [12]

2.3.3. Measurement Conditions

2.3.3.1. Temperature During Measurement

The concrete temperature during resistivity measurement can greatly affect the measured value. As the concrete temperature increases, the concrete resistivity measured typically decreases [4], [30], [63], [64]. This is partly because as the temperature increases, ions are more mobile in solution and can conduct electricity better [4]. Linear corrections have been used to normalize for this effect in narrow temperature ranges [65] but do not adequately account for temperature in unsaturated conditions or when low temperatures are used [66]. The Arrhenius approach has been shown however to adequately describe the effect of concrete temperature during resistivity measurement on the resistivity in saturated systems [64], as shown in Equation 14:

$$\frac{\rho_{Tref}}{\rho} = exp\left[\frac{E_{a,\rho}}{R}\left(\frac{1}{T} - \frac{1}{T_{ref}}\right)\right] \quad \text{Equation 14}$$

Where ρ_{Tref} is the concrete resistivity at the reference temperature T_{ref}, ρ is the measured concrete resistivity at temperature T, $E_{a,\rho}$ is the activation energy for resistivity, and R is the universal gas constant (8.314 J/mol/K). The activation energy for many different types of concrete has been reported to vary from 9 to 39 kJ/mol [67]. Equation 17 has been simplified somewhat in another study [64], as shown in Equation 15:

$$\rho_{Tref} = A \cdot \left[\frac{E_{a,\rho}}{R \cdot (T + 273.15)}\right] \quad \text{Equation 15}$$

Where A is the resistivity when the temperature goes to infinity. This approach can be used to normalize for the effects of concrete temperature if the activation energy is known and the concrete temperature is measured. A study of the concrete activation energy for resistivity found that the mixtures with higher resistivity were more affected by temperature during measurement. Equation 16 was developed to predict the activation energy for resistivity for concrete with ≥20% fly ash or ≥50% slag cement, while Equation 17 was developed for concrete without SCMs, with <20% fly ash, or <50% slag cement [64]:

$$E_{a,\rho} = 3.7738 \ln(\rho_{21}) + 9.7518 \quad \text{Equation 16}$$

$$E_{a,\rho} = 6.0157 \ln(\rho_{21}) + 4.3121 \quad \text{Equation 17}$$

Where ρ_{21} is the concrete equivalent resistivity at 69.8°F (21°C). Equation 16 and Equation 17 were combined to normalize the concrete bulk resistivity results to that measured at 69.8°F (21°C) in Equation 18 [64]:

$$\rho_{21} = 10 \cdot exp\left[\frac{\ln\left(\frac{10}{\rho_T}\right) \cdot T + 273.15 \cdot \ln\left(\frac{10}{\rho_T}\right) - 3.98755 \cdot T + 83.7385}{0.54312 \cdot T - 305.556}\right] \quad \text{Equation 18}$$

Where ρ_T is the resistivity at temperature T.

The concrete resistivity temperature dependence is partly a function of degree of saturation. As the degree of saturation decreases, the temperature sensitivity has been shown to increase. This means that the concrete temperature and saturation effects on resistivity, making corrections on resistivity based on each parameter individually only approximate [63]. Concrete pore solution has been shown to have an activation energy ranging from 7.7 kJ/mol to 13.9 kJ/mol [4], [26], [67], [68], [69]. Saturated concrete activation energy values for resistivity approach the pore solution activation energy for resistivity, whereas the activation energy for sealed concrete samples are close to double that of the saturated samples [66]. It was found that the degree of saturation may affect the concrete activation energy by reducing the degree of porosity connectivity [67]. Equation 19 shows an empirical relationship that was found that relates the concrete activation energy to the degree of saturation [67]:

$$E_{a-cond} = E_{a-sat} + \left(E_{a-0} \cdot (1 - S^n)\right) \quad \text{Equation 19}$$

Where E_{a-cond} is the activation energy of conduction, E_{a-sat} is the concrete activation energy at 100% degree of saturation, E_{a-0} is the fit value of activation energy at 0% degree of saturation, S is the degree of saturation, and n is a coefficient. E_{a-0} was found to be 6.96 and n to be 7.57 [67].

2.3.3.2. Sample Rinsing

Conductive solution on the surface of the concrete sample can conduct electricity and measure values lower than expected, especially with surface resistivity measurements. AASHTO T 358 requires the concrete surface be wiped with a wet sponge or towel to get the sample to a saturated surface dry state. This requires also the samples be tested within 5 minutes of removal from their curing environment to prevent it the surface from drying and giving higher measurements than they should be [36].

2.4. Resistivity as Acceptance Criterion

2.4.1. Electrical Resistivity Comparisons of Field and Laboratory-Produced Concrete

Few studies with a limited number of mixtures have been conducted to compare the electrical resistivity of concrete made in the laboratory and field. This may be because to date electrical resistivity tests have been used mostly as a qualification test instead of an acceptance test.

One study examined the electrical resistivity of concrete internally cured with presoaked lightweight aggregate and compared results from trial batches and field concrete. The electrical resistivities of sealed-cured samples were measured, after which the samples were vacuum saturated with limewater. The single-truck average coefficient of variation was found to be 4.8% at 28 days. The average sealed concrete resistivity from 6 cylinders made from each of 6 trucks sampled on the project were about 20% lower than the trial batch surface resistivity at 90 days. It was thought that this occurred because of a small increase in the w/cm. The trial batches were made with a 0.38 w/cm, whereas the concrete sampled from the trucks during construction had a w/cm of 0.394 [1], although this seems to be a large decrease in resistivity from a 0.014 increase in the w/cm.

Another study that was conducted at Utah State University compared the electrical resistivity of one concrete mixture in the field and laboratory. The field-produced concrete showed lower surface and bulk resistivity. The field surface resistivity was over 10 kΩ-cm or more than 50% lower at 56 days than that measured in the laboratory. The strength was also at least 2000 psi lower [3], indicating that the issue is not with the manner in which resistivity is tested on field samples, but with the concrete mixture delivered or in the sample transport and curing.

The third example found in the literature where the concrete resistivity from field samples was compared against laboratory-produced samples was from Oklahoma State University. 54 samples were evaluated comparing field-produced concrete to similar mixtures made in the laboratory. It was found that a majority of concrete mixtures produced in the field exhibited resistivity values lower than expected based on the laboratory samples. For one concrete producer for example, it was estimated that only 3 out of 22 samples were representative of the laboratory concrete used as control. The study concluded that the differences between laboratory and field samples were because the concrete field samples had too high of a w/cm and should be rejected. Some of the producers that made field samples that were compared to laboratory samples had high batch variability [2].

2.4.2. Known Impacts of Initial Curing on Strength

While few systematic studies of the effects of field curing on electrical resistivity properties have been conducted, several have been conducted on compressive strength development. Curing and handling variables known to affect the concrete strength include vibration or mishandling during transport, moisture loss, and unregulated curing temperatures.

2.4.2.1. Sample Handling

Concrete samples can be damaged during handling and transport if proper procedures are not followed. Concrete samples are to be placed in the location for initial curing with 15 minutes after finishing. They are not to be moved until at least 8 hours after final set because vibrations can cause microcracking. During transportation to the laboratory for final curing, the samples need to be protected from jarring or impact to prevent damage and should not have a transportation time greater than 4 hrs [70]. Damage to cylinders during transport would artificially lower the concrete resistivity measured.

2.4.2.2. Sample Initial Curing Temperature and Relative Humidity

Concrete cured using non-standard temperature and humidity conditions during the initial curing period in the molds can have a great impact on the concrete porosity and strength development. One study found that curing the concrete during the first day at standard temperature but at 60% relative humidity produced concrete 8% lower in strength than concrete cured at 100% relative humidity during the first day. Another study showed that concrete cylinders molded at 86°F in the field and covered with wet burlap and plastic and left outdoors for the first 24 hours experienced temperatures of between 94 and 140°F. Even though they were transferred to a standard moist curing room at 24 hours, they had 17% lower strength than the control samples cured in a cure box with thermostatic control [71].

A study was performed by the Nebraska Department of Transportation to examine the effects of different cylinder temperature protection methods during initial field curing. For hot weather, they compared a cooler with water, metal box with insulation cut out for the cylinders, cooler in shade with and without burlap, cylinders in direct sunlight, and a wood box with insulation. They found that the cooler with water gave the highest 3-, 7- and 14-day strengths, while cylinders in direct sunlight had the lowest 3-, 7-, and 14-day strengths. The 14-day strength for the cylinders cured in the cooler with water was 4050 psi, whereas the 14-day strength for the cylinders cured in direct sunlight in hot weather was 2890 psi. They recommended curing cylinders in coolers with water covering at least 75% of the cylinder when the temperature is above 80°F [72].

2.5. Summary

Electrical resistivity measurements have been shown to correlate well with concrete transport properties and have served well as a concrete mixture qualification test for many years. Several standardized tests have been developed to measure the concrete electrical properties. These tests mainly vary in the sample geometry configuration, how they cure the sample, and how the samples are conditioned for testing and can result in correlated but different results. Relative humidity and temperature used during initial concrete curing is thought to be important for concrete property development and could result in low resistivity measurements. Concrete samples are especially sensitive in electrical resistivity testing to leaching that occurs during curing and degree of saturation and temperature during curing and testing. Concrete resistivity meter model and frequency used in the ranges specified in standardized test methods have not been found to produce statistically different results. Limited electrical resistivity comparisons of field- and laboratory-made samples showed that field-made samples often had lower electrical resistivity values. This was mostly attributed to higher-than-approved w/cm in field-produced concrete.

3. CONCRETE SAMPLING AND SPECIMEN FABRICATION

3.1. Introduction

Electrical resistivity test methods are used to estimate concrete chloride ion penetrability [73] and therefore rating protection of concrete members against corrosion. The Florida Department of Transportation currently uses a 29 kΩ-cm surface resistivity limit to approve mixes that include highly reactive pozzolans [74]. To determine if and how an electrical resistivity test could be used for field quality control measurements, the variability in electrical resistivity measurements between concrete specimens fabricated under field and laboratory conditions were studied. For this purpose, 15 concrete placements from several construction sites around Florida were visited to fabricate concrete specimens from concrete placements on site. Materials used to produce the concrete delivered to the concrete placements were collected, and mix designs were recreated under laboratory conditions. The following report presents information about the construction sites visited, mix designs used, concrete fresh properties obtained from the concrete placement, temperature information for the initial curing of the specimens from the laboratory and field, and specimen dimensions.

3.2. Methodology

Concrete specimens were collected from concrete placements of structural members for 15 concrete mix designs at 11 FDOT construction sites in Florida. At each construction site visited, concrete was collected from two separate trucks on each site following ASTM C172 [75], concrete temperature was measured following ASTM C1064 [76], and concrete slump was measured following ASTM C143 [77]. The unit weight was measured following ASTM C138 [78]. Concrete air content was measured following ASTM C231 [79]. 24 - 4 in. × 8 in. concrete specimens were fabricated following ASTM C192 [80], 12 from each truck sampled. 2 additional concrete specimens of the same size were also fabricated to measure the temperature that the concrete developed in the initial curing phase under different initial curing temperature conditions.

Half of the specimens were field cured following ASTM C31. The other half of the specimens were cured in an insulated box (cooler) filled with water up to 3/4 of the height of the cylinders, as recommended in [81], that was conditioned with ice to be at the start of the curing period to be at the lower bound of the 60 °F to 80 °F temperature limits in ASTM C31 for concrete of less than 6000 psi. It was anticipated that the samples would be within the curing temperature limits specified during most of the initial 24-48 hrs of curing time.

Materials used to produce the concrete delivered to the concrete placements were collected after the construction site visits. Twenty-four 4 in. × 8 in. concrete cylinders were fabricated under laboratory conditions according to ASTM C192 [80] for each of the mixtures sampled in the field using the same mixture design as that used in the field. Two additional 4 in. × 8 in. concrete specimens were also fabricated to measure the temperature that the concrete developed in the initial curing phase under different curing temperatures. The same test methods used to measure the concrete fresh properties in the field site visits were used for the mixtures made in the laboratory. Half of the specimens were cured inside the laboratory representing a temperature-controlled environment and the other half were cured outside of the laboratory. Air temperatures for both initial curing conditions were recorded as well as temperature developed by concrete in each of the curing systems. Table 2 shows the different specimen treatment conditions used for each specimen number.

Table 2. Factors to be tested for each site visited

Factor	Determination Number							
	1 (9)	2 (10)	3 (11)	4 (12)	5 (13)	6 (14)	7 (15)	8 (16)
A. Electrical resistivity measurement frequency	40	100	100	40	100	40	40	100
B. Temperature control before demolding	Uninsulated box	Uninsulated box	Cooler with Tempered Water	Cooler with Tempered Water	Uninsulated box	Cooler with Tempered Water	Uninsulated box	Cooler with Tempered Water
C. Time between sample fabrication and demolding	24-48 hrs	24-48 hrs	24-48 hrs	7 days	7 days	24-48 hrs	7 days	7 days
D. Limewater	Communal	Individual	Individual	Individual	Communal	Communal	Individual	Communal
E. Sample moisture state during testing	Dry	Wet	Dry	Wet	Wet	Wet	Dry	Dry
F. Sample production	Lab	Lab	Field	Lab	Field	Field	Field	Lab

3.3. Concrete Mixtures Sampled

Fifteen concrete mixtures were sampled in the field at 11 different Florida Department of Transportation construction sites.

3.3.1. Concrete Mixture 1

The first construction site visited to sample concrete was the SR 23 First Coast Expressway project in Jacksonville, FL on October 11, 2022. A picture of the concrete placement can be seen in Figure 10.

Figure 10. Placement of the first concrete mixture sampled

Mixture proportions for the first concrete mixture sampled are shown in Table 3. The concrete mixture was designed to meet FDOT class IV concrete with a minimum strength of 5500 psi. The fresh properties measured in the field are shown in Table 4. The curing temperatures recorded in the field during curing are shown in Figure 11.

Table 3. Concrete mix design information for mixture 1

Material	Quantity	Unit
Cement - Type IL	455	lb/yd^3
Fly Ash - Class F	245	lb/yd^3
#57 Stone	1600	lb/yd^3
Silica Sand	1283	lb/yd^3
Air Entraining Admixture	2.0	$fl\ oz/yd^3$
Type D Water Reducing and Retarding Admixture	35	$fl\ oz/yd^3$
Type F High Range Water Reducing Admixture	17.9	$fl\ oz/yd^3$
Water	238	lb/yd^3

Table 4. Fresh properties measured in the field for mixture 1

Test	Sample 1	Sample 2
Slump (in)	6.5	8.0
Concrete temperature at placement (°F)	86	84
Unit Weight (lb/ft^3)	144.8	143.4
Air Content, %	1.8%	2.3%

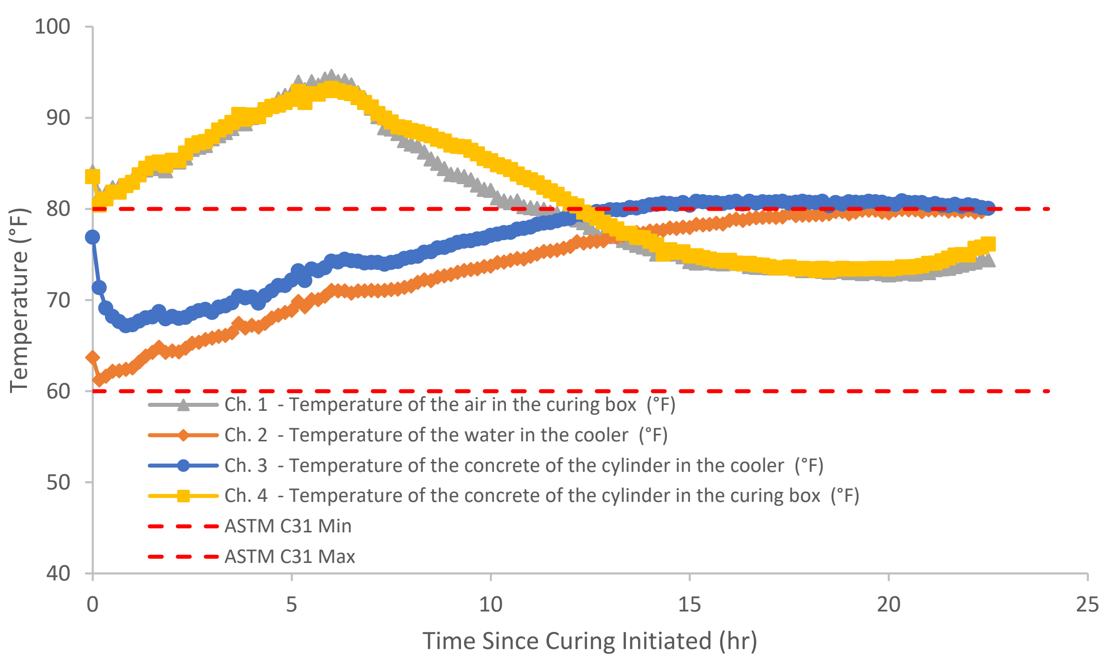

Figure 11. Curing temperatures measured for the field sampling for mixture 1

The concrete sampled in the field was reproduced under laboratory conditions with the materials collected from the ready-mixed concrete plant. The fresh properties measured from the concrete reproduced in the laboratory are shown in Table 5. The curing temperatures recorded during curing for the laboratory-made concrete are shown in Figure 12. Specimen dimensions for the concrete cylinders made in the field and laboratory are shown in Table 6.

Table 5. Fresh properties measured in the laboratory for mixture 1

Test	**Batch 1**	**Batch 2**
Slump (in)	3.5	3.5
Concrete temperature at placement (°F)	74	74
Unit Weight (lb/ft^3)	144.0	143.4
Air Content, %	2.4%	1.8%

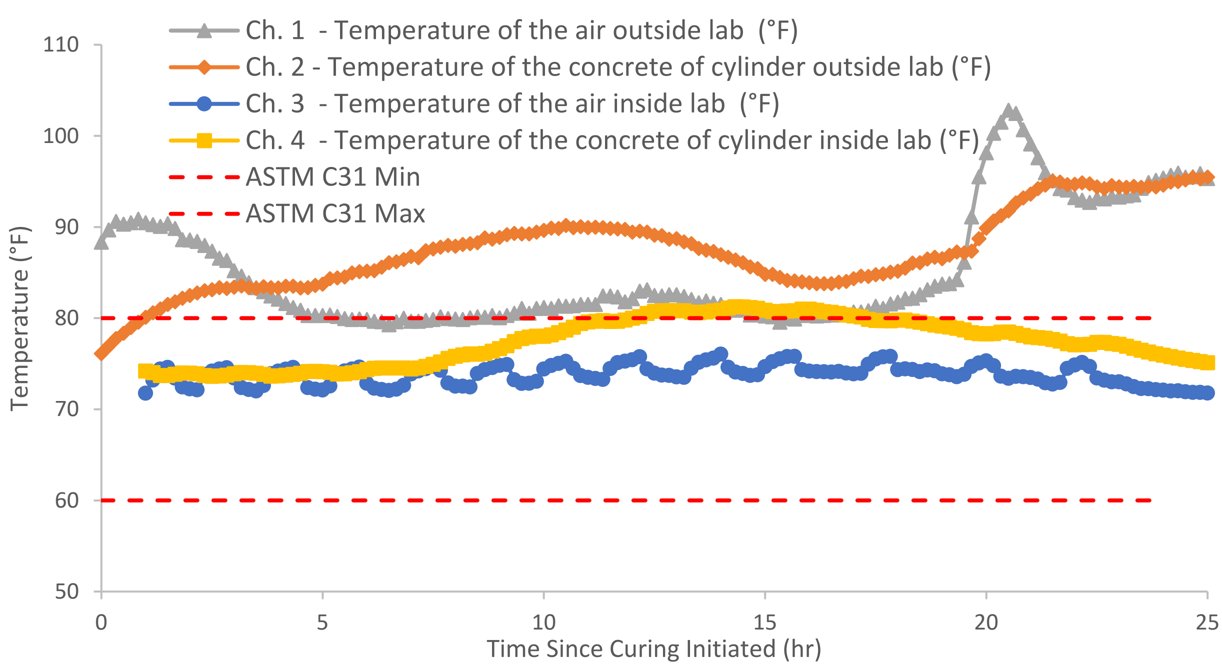

Figure 12. Temperatures measured during curing for samples made in the laboratory for mixture 1

Table 6. Specimen dimensions for concrete cylinders made for mixture 1

Cylinder		Determination															
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**
1	**Average Diameter (mm)**	101.7	101.7	102.1	101.4	101.7	101.7	103.0	101.7	101.7	101.5	102.8	101.5	101.7	101.6	103.0	101.8
	Average Length (mm)	191.5	198.8	196.8	196.3	194.7	194.7	197.2	190.6	189.5	198.4	198.7	196.2	196.3	197.9	161.7	196.4
2	**Average Diameter (mm)**	101.6	101.6	101.8	101.4	101.8	101.8	102.7	101.5	101.9	101.8	102.0	101.7	101.9	101.7	102.4	101.5
	Average Length (mm)	191.7	197.5	196.5	197.8	195.9	195.9	195.2	190.6	191.9	198.3	195.4	196.9	193.5	196.8	198.5	196.7
3	**Average Diameter (mm)**	101.7	101.8	101.8	101.7	101.8	101.8	102.6	101.6	101.7	101.6	101.7	101.4	101.9	101.6	102.8	101.3
	Average Length (mm)	193.2	197.6	197.8	197.9	197.5	197.5	196.1	189.8	191.7	200.1	195.5	196.9	193.7	199.0	197.7	199.3

3.3.2. Concrete Mixture 2

Concrete mixture 2 was sampled near Jacksonville, FL on December 9, 2022. Mixture proportions for the first concrete mixture sampled are shown in Table 7. The fresh properties measured in the field are shown in Table 8. The curing temperatures recorded in the field from the specimens and curing environment are shown in Figure 13.

Table 7. Concrete mix design information for mixture 2

Material	Quantity	Unit
Cement - Type IL	560	lb/yd^3
Fly Ash - Class F	140	lb/yd^3
#57 Stone	1700	lb/yd^3
Silica Sand	1090	lb/yd^3
Air Entraining Admixture	9.0	fl oz/yd^3
Admixture for Concrete Type D Water - Reducing and Retarding	35.0	fl oz/yd^3
Water	280	lb/yd^3

Table 8. Field fresh properties construction site 1

Test	Sample 1	Sample 2
Slump (in)	5.25	5.0
Concrete temperature at placement (°F)	84	85
Unit Weight (lb/ft3)	141.4	143.2
Air Content, %	0.9%	0.9%

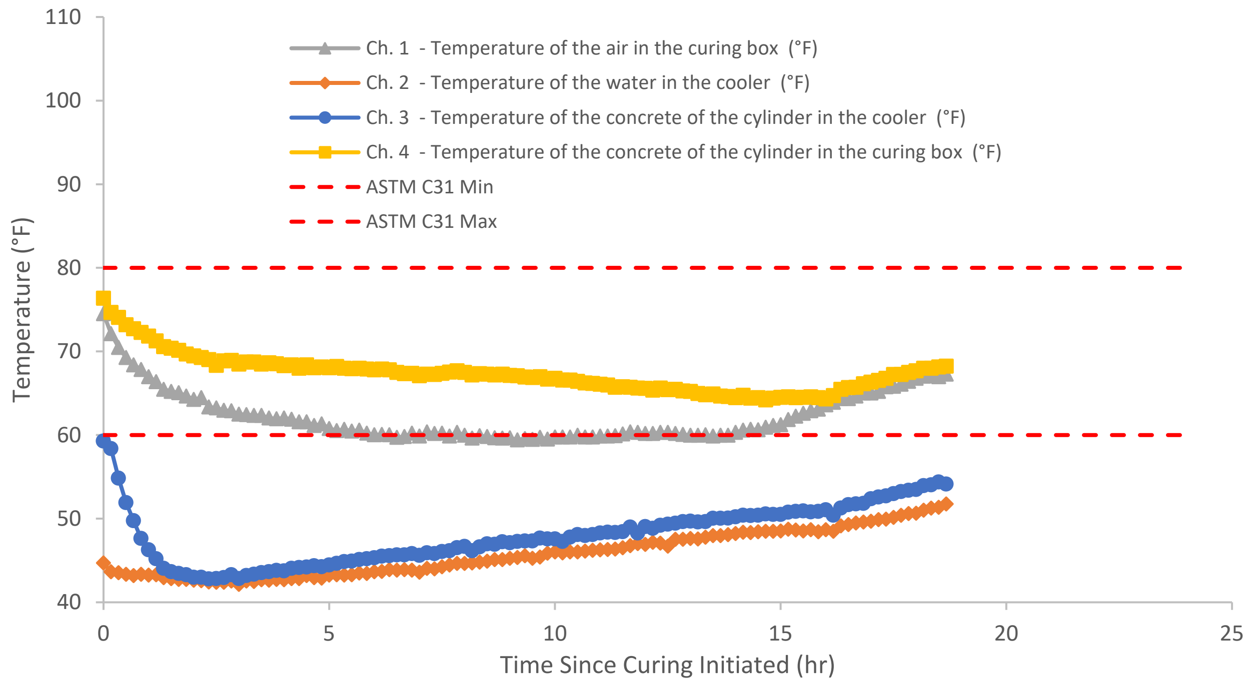

Figure 13. Curing temperatures measured for the field sampling for mixture 2

Concrete mixture 2 was reproduced under laboratory conditions with the materials collected from the ready-mix plant. The fresh properties measured from the reproduced mix in the laboratory are shown in Table 9. The curing temperatures recorded from the laboratory conditions from the specimens are shown in Figure 14. The dimensions from the specimens fabricated are shown in Table 10.

Table 9. Fresh properties measured in the laboratory for mixture 2

Test	**Batch 1**	**Batch 2**
Slump (in)	4.0	4.5
Concrete temperature at placement (°F)	75	74
Unit Weight (lb/ft^3)	141.4	139.0
Air Content, %	3.0%	3.8%

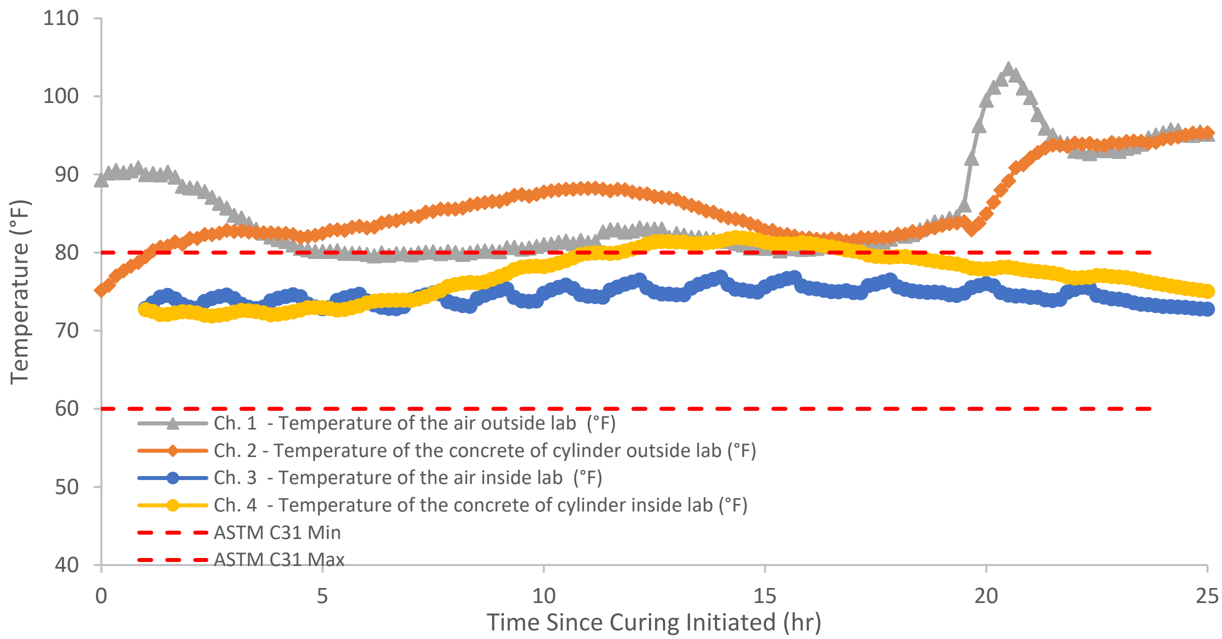

Figure 14. Temperatures measured during curing for samples made in the laboratory for mixture 2

Table 10. Specimen dimensions for concrete cylinders made for mixture 2

Cylinder		Determination															
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**
1	**Average Diameter (mm)**	101.9	101.6	101.9	101.6	101.6	101.8	101.9	101.9	101.7	101.6	101.4	101.2	131.8	101.8	101.6	101.7
	Average Length (mm)	196.1	194.9	198.2	194.3	200.8	196.6	198.0	194.2	197.2	196.6	199.7	194.4	199.9	200.3	196.3	196.5
2	**Average Diameter (mm)**	101.8	101.8	101.6	101.7	101.7	101.5	198.1	101.5	101.7	101.8	101.4	101.3	101.6	101.8	101.5	101.6
	Average Length (mm)	195.7	195.4	198.2	196.3	198.2	199.6	102.0	195.9	195.8	197.1	199.8	195.1	198.2	200.5	196.5	195.5
3	**Average Diameter (mm)**	101.9	101.6	101.7	101.8	101.8	101.8	101.8	101.7	101.7	101.4	101.4	101.4	101.7	101.5	102.1	101.8
	Average Length (mm)	195.3	194.2	200.7	194.7	200.3	196.6	196.8	196.5	196.8	196.7	200.8	192.1	197.2	200.2	197.8	196.2

3.3.3. Concrete Mixture 3

Concrete mixture 3 was sample from a construction site in Titusville, FL on January 13, 2023. Mixture proportions for the first concrete mixture sampled are shown in Table 11. The concrete mixture was designed to meet FDOT class IV concrete with a minimum strength of 5500 psi. The fresh properties measured in the field are shown in Table 12. The curing temperatures recorded in the field during curing are shown in Figure 15.

Table 11. Concrete mix design information for mixture 3

Material	**Quantity**	**Unit**
Cement - Type II (MH)	221	lb/yd^3
Slag	369	lb/yd^3
Fly Ash	148	lb/yd^3
#57 Stone	1757	lb/yd^3
Silica Sand	1069	lb/yd^3
Air Entraining Admixture	0.1	fl oz/yd^3
Admixture for Concrete Type D Water - Reducing and Retarding	26.5	fl oz/yd^3
Admixture for Concrete Type F High Range - Water Reducing	22.1	fl oz/yd^3
Water	258	lb/yd^3

Table 12. Fresh properties measured in the field for mixture 3

Test	**Sample 1**	**Sample 2**
Slump (in)	7.25	8.5
Concrete temperature at placement (°F)	71	71
Unit Weight (lb/ft3)	142.8	142.7
Air Content, %	0.5%	0.5%

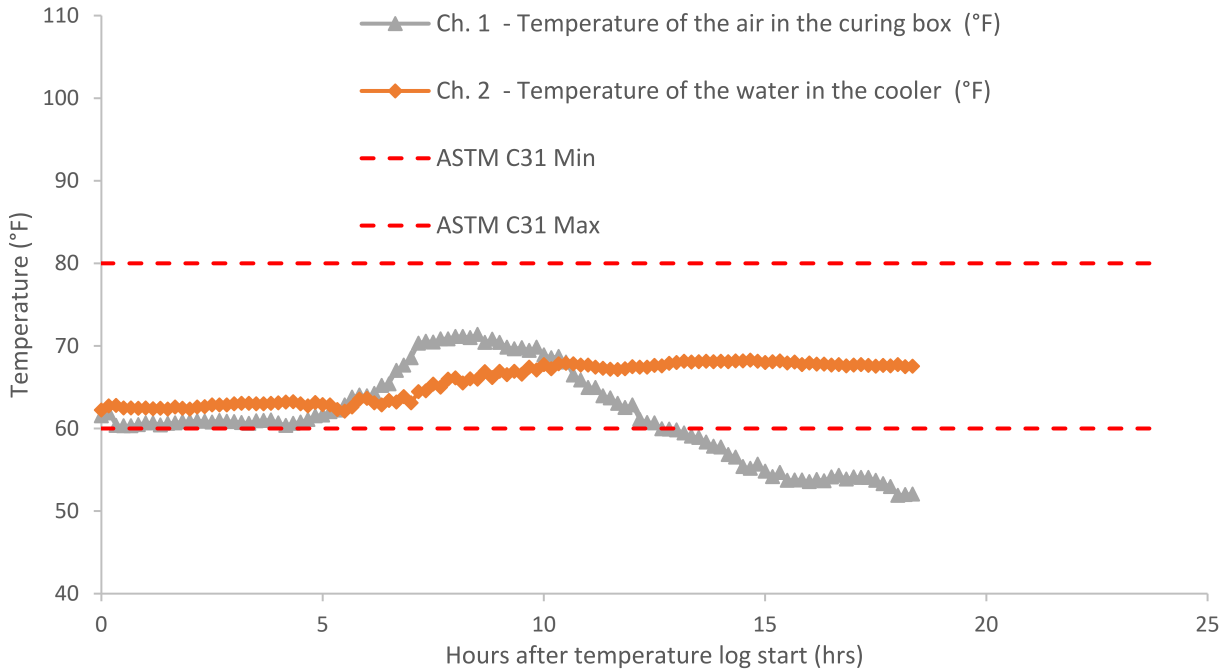

Figure 15. Curing temperatures measured for the field sampling for mixture 3

The concrete sampled in the field was reproduced under laboratory conditions with the materials collected from the ready-mixed concrete plant. The fresh properties measured from the reproduced mix in the laboratory are shown in Table 13. The curing temperatures recorded during curing for the laboratory-made concrete are shown in Figure 16. Specimen dimensions for the concrete cylinders made in the field and laboratory are shown in Table 14.

Table 13. Fresh properties measured in the laboratory for mixture 3

Test	Batch 1	Batch 2
Slump (in)	9.0	9.0
Concrete temperature at placement (°F)	78	78
Unit Weight (lb/ft^3)	147.3	147.8
Air Content, %	0.3%	0.2%

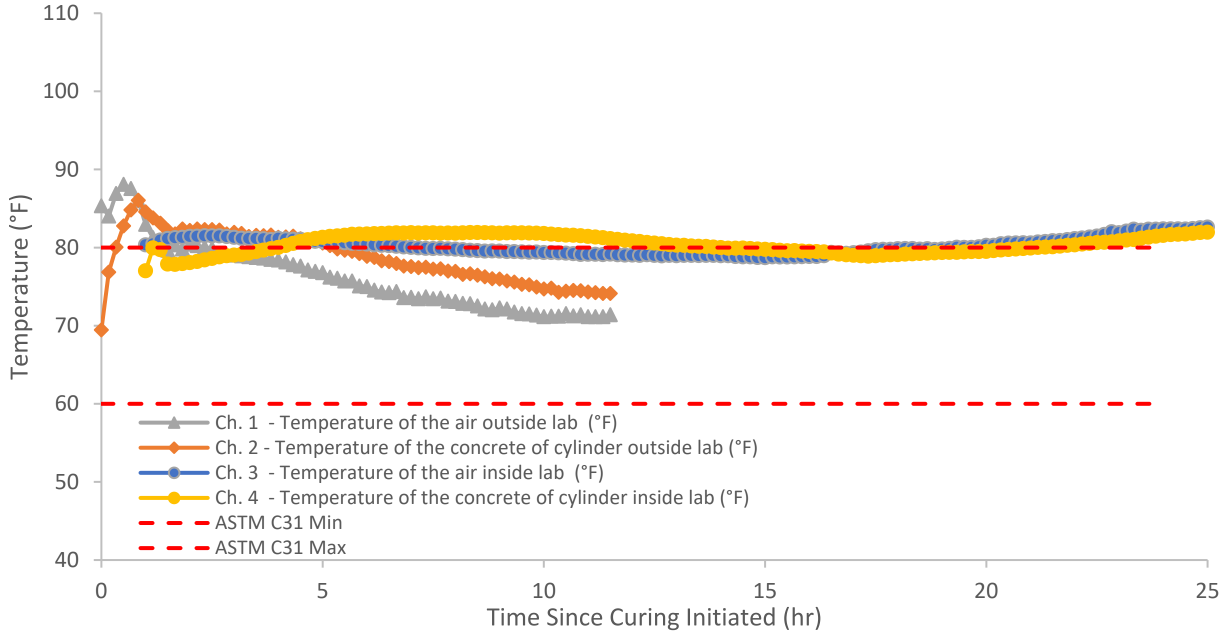

Figure 16. Temperatures measured during curing for samples made in the laboratory for mixture 3

Table 14. Specimen dimensions for concrete cylinders made for mixture 3

Cylinder		Determination															
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1	Average Diameter (mm)	101.5	101.9	101.2	101.7	101.6	101.2	101.7	101.3	101.6	101.6	101.6	102.2	101.6	101.6	101.6	101.6
	Average Length (mm)	193.6	196.4	194.8	195.4	194.5	195.6	193.1	196.0	197.0	197.0	197.4	198.0	197.1	197.0	195.7	198.7
2	Average Diameter (mm)	101.5	101.6	101.4	94.1	101.8	101.7	101.6	101.4	101.8	101.8	101.2	102.0	101.5	102.0	101.7	101.7
	Average Length (mm)	193.7	197.5	195.0	187.8	195.4	194.2	195.9	197.0	195.8	195.8	198.0	195.0	197.9	197.3	198.7	198.1
3	Average Diameter (mm)	101.3	102.0	101.7	101.9	101.9	101.6	Not fabr.	101.6	102.0	102.0	101.7	101.8	Not fabr	101.6	103.0	101.6
	Average Length (mm)	194.3	194.8	197.2	193.7	195.3	196.1	Not fabr.	195.6	194.9	194.9	197.1	196.5	Not fabr.	194.8	196.9	198.5

3.3.4. Concrete Mixture 4

Concrete mixture 4 was sampled from a construction site in Titusville, FL on January 23, 2023. The mixture proportions are shown in Table 15. The concrete mixture was designed to meet FDOT class IV concrete with a minimum strength of 5500 psi. The fresh properties measured in the field are shown in Table 16. The curing temperatures recorded in the field during curing are shown in Figure 17.

Table 15. Concrete mix design information for mixture 4

Product	**Quantity**	**Units**
Cement - Type II (MH)	300	lb/yd^3
Slag	420	lb/yd^3
#57 Stone	1736	lb/yd^3
Silica Sand	1130	lb/yd^3
Air Entraining Admixture	0.1	$fl\ oz/yd^3$
Admixture for Concrete Type D Water - Reducing and Retarding	30.0	$fl\ oz/yd^3$
Admixture for Concrete Type F High Range - Water Reducing	30.0	$fl\ oz/yd^3$
Water	267	lb/yd^3

Table 16. Fresh properties measured in the field for mixture 4

Test	**Sample 1**	**Sample 2**
Slump (in)	5.75	8.75
Concrete temperature at placement (°F)	75	80
Unit Weight (lb/ft3)	143.3	144.2
Air Content, %	1.0%	1.3%

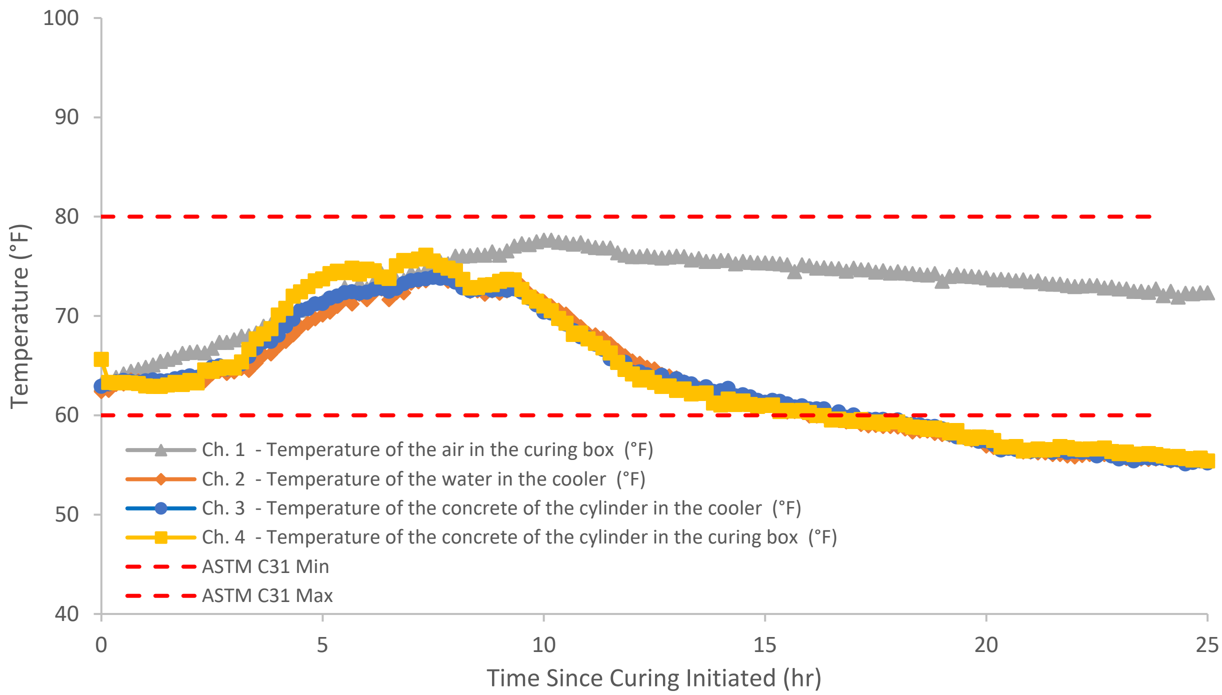

Figure 17. Curing temperatures measured for the field sampling for mixture 4

The concrete sampled in the field was reproduced under laboratory conditions with the materials collected from the ready-mixed concrete plant. The fresh properties measured from the reproduced mix in the laboratory are shown in Table 17. The temperatures recorded during curing for the laboratory-made concrete are shown in Figure 18. Specimen dimensions for the concrete cylinders made in the field and laboratory are shown Table 18.

Table 17. Fresh properties measured in the laboratory for mixture 4

Test	**Batch 1**	**Batch 2**
Slump (in)	10.0	9.75
Concrete temperature at placement (°F)	71	71
Unit Weight (lb/ft^3)	146.3	146.5
Air Content, %	0.4%	0.5%

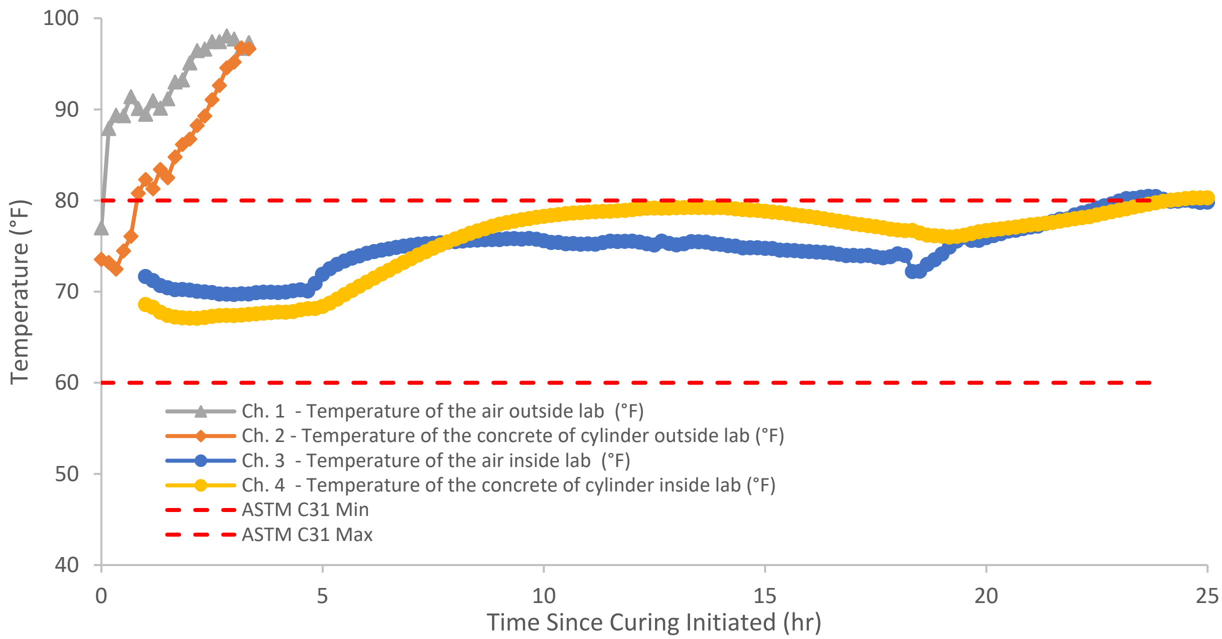

Figure 18. Temperatures measured during curing for samples made in the laboratory for mixture 4

Table 18. Specimen dimensions for concrete cylinders made for mixture 4

Cylinder		**Determination**															
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**
1	**Average Diameter (mm)**	101.9	101.7	101.8	101.6	101.9	102.3	102.3	101.7	101.9	101.6	102.0	101.9	101.8	101.5	101.8	101.6
	Average Length (mm)	195.4	196.8	199.3	196.8	196.4	201.7	201.7	193.8	191.5	195.3	199.8	196.3	196.9	199.7	198.6	194.9
2	**Average Diameter (mm)**	101.8	101.8	101.8	101.5	101.6	101.6	101.6	101.7	101.8	101.8	101.4	101.7	100.9	101.7	101.8	101.6
	Average Length (mm)	194.8	191.3	198.8	165.2	197.2	199.3	199.3	195.4	192.7	195.7	200.0	196.9	100.9	196.8	199.0	193.4
3	**Average Diameter (mm)**	101.8	101.9	101.8	101.3	101.8	101.5	101.5	101.6	101.7	101.7	101.7	101.5	101.7	101.1	101.8	101.4
	Average Length (mm)	195.2	195.2	199.3	195.6	198.7	199.4	199.4	194.6	194.9	196.9	197.9	196.6	198.3	196.2	198.7	195.8

3.3.5. Concrete Mixture 5

Concrete mixture 5 was sampled from a construction site in Tampa, FL on February 14, 2023. The mixture proportions are shown in Table 19. The concrete mixture was designed to meet FDOT class IV concrete with a minimum strength of 5500 psi. The fresh properties measured in the field are shown in Table 20. The curing temperatures recorded in the field during curing are shown in Figure 19.

Table 19. Concrete mix design information for mixture 5

Product	Quantity	Units
Cement - Type IL	266	lb/yd^3
Slag	399	lb/yd^3
#57 Stone	1698	lb/yd^3
Silica Sand	1164	lb/yd^3
Air Entraining Admixture	0.1	$fl\ oz/yd^3$
Admixture for Concrete Type D Water - Reducing and Retarding	66.5	$fl\ oz/yd^3$
Admixture for Concrete Type F High Range - Water Reducing	18.6	$fl\ oz/yd^3$
Water	267	lb/yd^3

Table 20. Fresh properties measured in the field for mixture 5

Test	Sample 1	Sample 2
Slump (in)	7.5	8.50
Concrete temperature at placement (°F)	69	70
Unit Weight (lb/ft^3)	141.8	140.7
Air Content, %	1.2%	1.3%

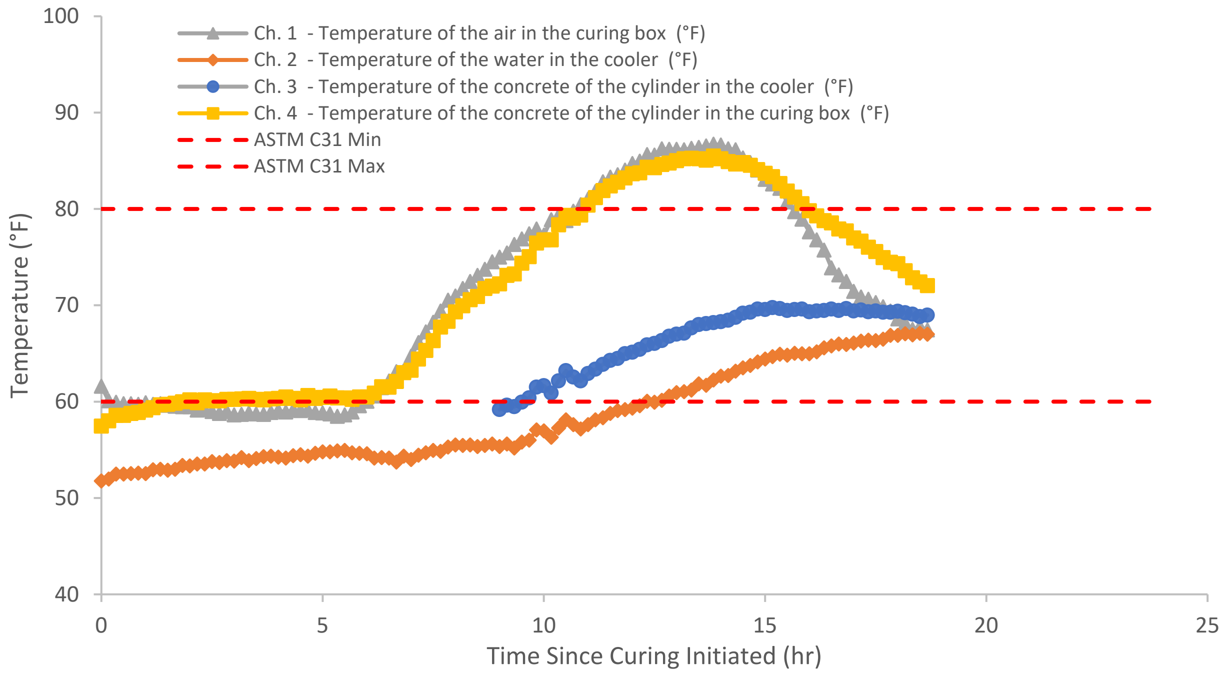

Figure 19. Curing temperatures measured for the field sampling for mixture 5

The concrete sampled in the field was reproduced under laboratory conditions with the materials collected from the ready-mixed concrete plant. The fresh properties measured from the reproduced mix in the laboratory are shown in Table 21. The curing temperatures recorded during curing for the laboratory-made concrete are shown in Figure 20. Specimen dimensions for the concrete cylinders made in the field and laboratory are shown in Table 22.

Table 21. Fresh properties measured in the laboratory for mixture 5

Test	Batch 1	Batch 2
Slump (in)	9.25	10.5
Concrete temperature at placement (°F)	77	77
Unit Weight (lb/ft^3)	143.8	143.8
Air Content, %	1.9%	2.8%

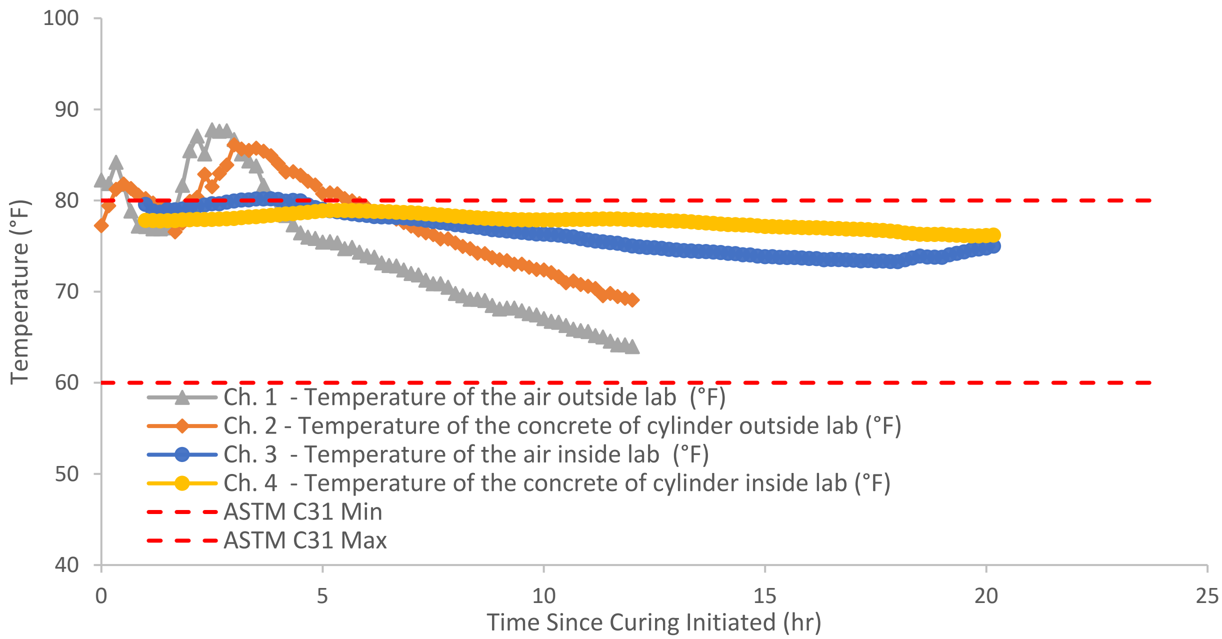

Figure 20. Temperatures measured during curing for samples made in the laboratory for mixture 5

Table 22. Specimen dimensions for concrete cylinders made for mixture 5

Cylinder		**Determination**															
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**
1	**Average Diameter (mm)**	101.7	101.7	101.9	101.7	101.4	101.5	101.8	101.7	101.6	101.6	101.8	99.2	101.8	101.6	101.3	99.2
	Average Length (mm)	195.1	192.2	195.9	190.4	196.8	194.6	196.3	194.7	192.3	192.3	196.3	189.0	196.7	197.2	196.4	189.0
2	**Average Diameter (mm)**	101.8	101.6	101.5	101.9	101.7	101.4	101.8	101.9	101.6	101.6	101.8	99.1	102.0	Not fabr	101.6	99.1
	Average Length (mm)	193.9	195.8	194.1	193.1	196.8	197.4	196.3	193.9	193.0	193.0	196.7	189.8	197.6	Not fabr	196.9	189.8
3	**Average Diameter (mm)**	102.3	101.8	101.9	101.5	101.6	Not fabr	101.5	101.9	101.7	101.7	102.2	99.3	101.5	Not fabr	101.7	99.3
	Average Length (mm)	194.2	191.2	194.4	191.8	196.9	Not fabr	198.8	194.4	192.0	192.0	195.5	191.0	197.7	Not fabr	198.0	191.0

3.3.6. Concrete Mixture 6

Concrete for mixture 6 was sampled from a construction site in Tampa, FL on February 28, 2023. The concrete mixture proportions for mixture 6 are shown in Table 23. The concrete mixture was designed to meet FDOT class IV concrete with a minimum strength of 5500 psi. The concrete fresh properties measured in the field are shown in Table 24. The temperatures recorded in the field during curing are shown in Figure 21.

Table 23. Concrete mix design information for mixture 6

Product	**Quantity**	**Units**
Cement - Type IL	326	lb/yd^3
Slag	339	lb/yd^3
#57 Stone	1700	lb/yd^3
Silica Sand	1180	lb/yd^3
Air Entraining Admixture	0.1	$fl\ oz/yd^3$
Admixture for Concrete Type D Water - Reducing and Retarding	66.5	$fl\ oz/yd^3$
Admixture for Concrete Type F High Range - Water Reducing	26.1	$fl\ oz/yd^3$
Water	262	lb/yd^3

Table 24. Fresh properties measured in the field for mixture 1

Test	**Sample 1**	**Sample 2**
Slump (in)	7.5	8.5
Concrete temperature at placement (°F)	82	84
Unit Weight (lb/ft3)	143.4	143.4
Air Content, %	2.3%	2.2%

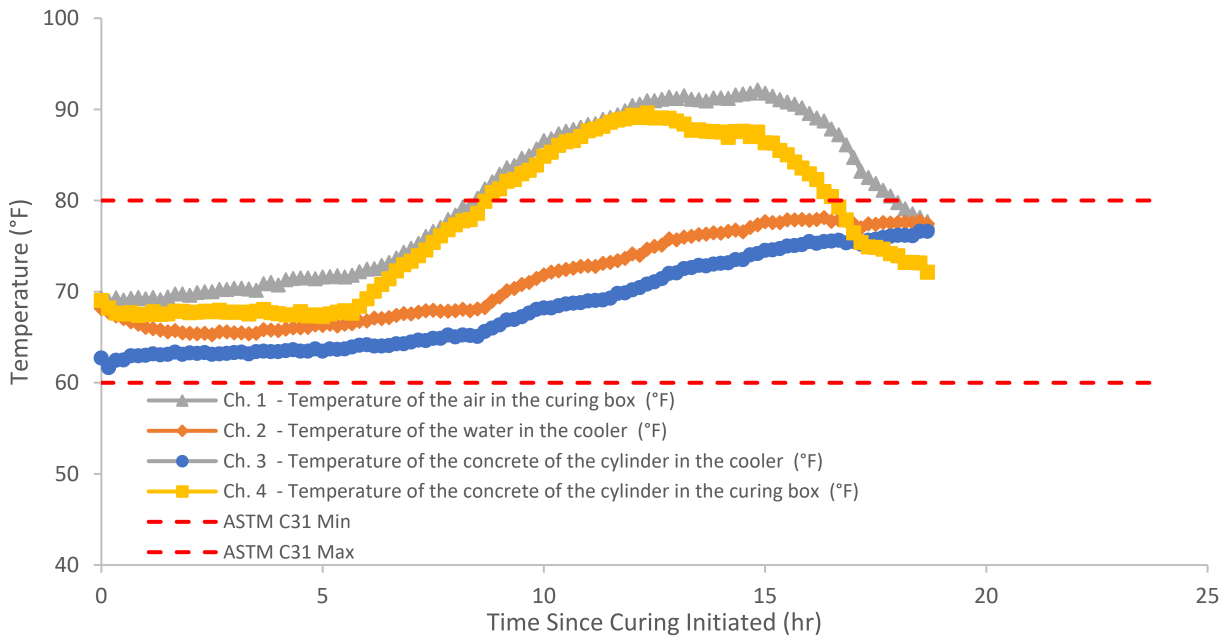

Figure 21. Curing temperatures measured for the field sampling for mixture 6

The concrete sampled in the field was reproduced under laboratory conditions with the materials collected from the ready-mixed concrete plant. The fresh properties measured from the reproduced mix in the laboratory are shown in Table 25. The temperatures recorded during curing for the laboratory-made concrete are shown in Figure 22. Specimen dimensions for the concrete cylinders made in the field and laboratory are shown in Table 26.

Table 25. Fresh properties measured in the laboratory for mixture 6

Test	**Sample 1**	**Sample 2**
Slump (in)	9.25	8.75
Concrete temperature at placement (°F)	77	77
Unit Weight (lb/ft^3)	146.5	143.8
Air Content, %	2.4%	2.6%

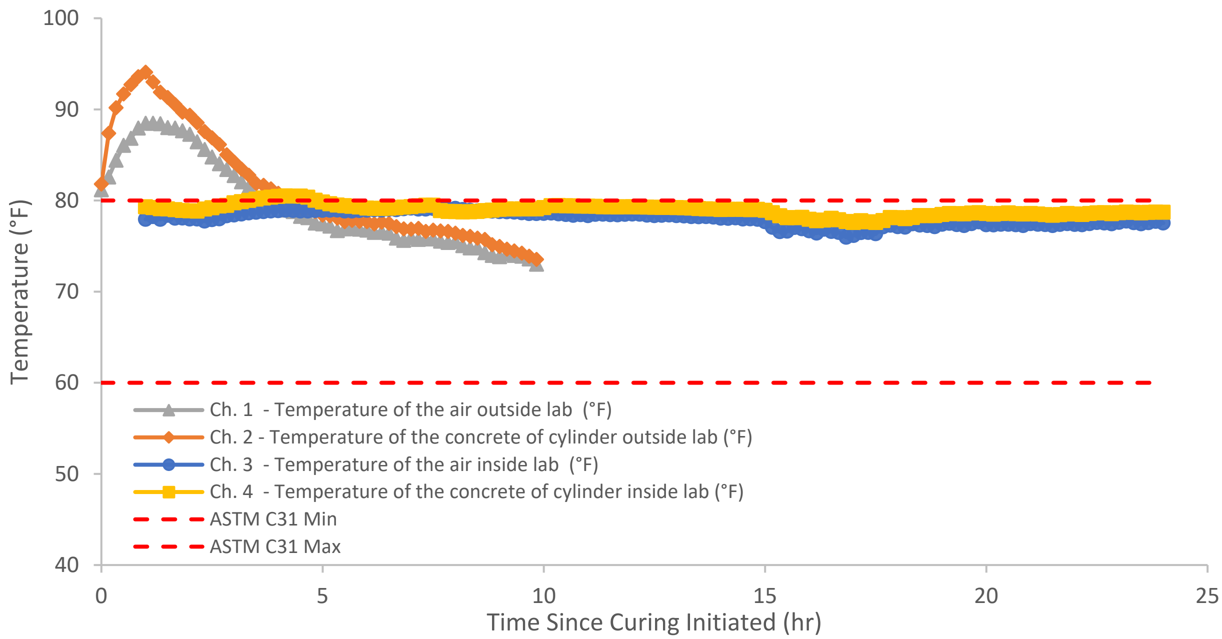

Figure 22. Temperatures measured during curing for samples made in the laboratory for mixture 6

Table 26. Specimen dimensions for concrete cylinders made for mixture 6

Cylinder		Determination															
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**
1	**Average Diameter (mm)**	101.7	101.7	101.4	101.5	101.5	101.7	101.9	101.6	101.5	101.7	101.9	101.5	101.7	100.0	197.2	101.6
	Average Length (mm)	193.7	194.9	195.4	197.9	197.6	196.2	196.4	197.0	195.1	196.5	197.7	198.2	196.0	200.0	197.2	197.5
2	**Average Diameter (mm)**	101.5	101.4	101.6	101.4	101.5	101.5	101.6	101.8	101.8	101.6	101.8	101.7	101.7	100.0	102.0	101.6
	Average Length (mm)	197.4	196.7	195.7	194.2	195.5	195.4	198.4	198.9	195.5	197.7	200.4	199.3	195.4	200.0	197.0	199.7
3	**Average Diameter (mm)**	101.6	101.8	101.8	101.6	101.5	101.3	101.9	101.7	101.6	101.5	101.6	101.6	101.2	100.0	101.5	101.9
	Average Length (mm)	196.6	197.3	193.3	196.6	198.4	195.2	197.8	198.9	196.2	197.5	197.2	196.5	196.2	200.0	196.2	198.1

3.3.7. Concrete Mixture 7

Concrete for mixture 7 was sampled from a construction site in Gainesville, FL on March 15, 2023. The mixture proportions are shown in Table 27. The concrete mixture was designed to meet FDOT class IV concrete requirements with a minimum strength of 4000 psi. The fresh properties measured in the field are shown in Table 28. The curing temperatures recorded in the field during curing are shown in Figure 23.

Table 27. Concrete mix design information for mixture 7

Product	**Quantity**	**Units**
Cement - Type IL	480	lb/yd^3
Fly Ash - Class F	258	lb/yd^3
#57 Stone	1609	lb/yd^3
Silica Sand	1089	lb/yd^3
Air Entraining Admixture	1.7	$fl\ oz/yd^3$
Admixture for Concrete Type D Water - Reducing and Retarding	59.3	$fl\ oz/yd^3$
Admixture for Concrete Type A Water Reducing	15	$fl\ oz/yd^3$
Water	300	lb/yd^3

Table 28. Fresh properties measured in the field for mixture 7

Test	**Sample 1**	**Sample 2**
Slump (in)	8.75	8.0
Concrete temperature at placement (°F)	75	75
Unit Weight (lb/ft3)	141.8	141.8
Air Content, %	0.1%	0.1%

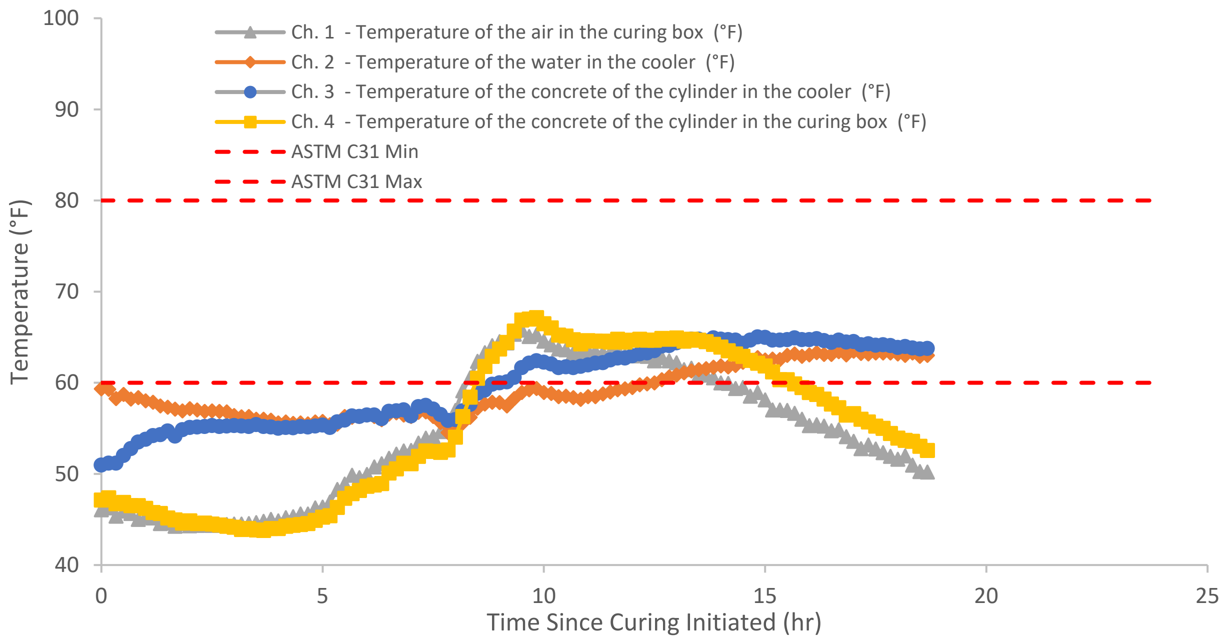

Figure 23. Curing temperatures measured for the field sampling for mixture 7

The concrete sampled in the field was reproduced under laboratory conditions with the materials collected from the ready-mixed concrete plant. The fresh properties measured from the reproduced mix in the laboratory are shown in Table 29. The temperatures recorded during curing for the laboratory-made concrete are shown in Figure 24. Specimen dimensions for the concrete cylinders made in the field and laboratory are shown in Table 30.

Table 29. Fresh properties measured in the laboratory for mixture 7

Test	**Batch 1**	**Batch 2**
Slump (in)	9.25	8.75
Concrete temperature at placement (°F)	74	75
Unit Weight (lb/ft^3)	142.8	142.5
Air Content, %	0.2%	0.2%

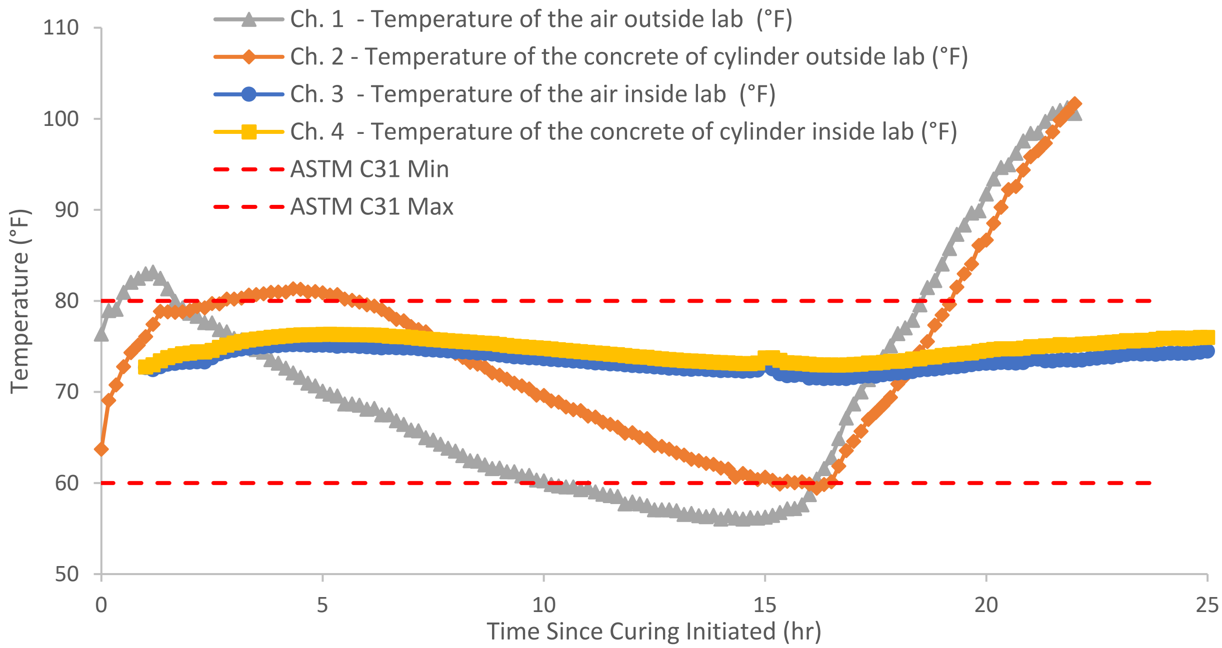

Figure 24. Temperatures measured during curing for samples made in the laboratory for mixture 7

Table 30. Specimen dimensions for concrete cylinders made for mixture 7

Cylinder		**Determination**															
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**
1	**Average Diameter (mm)**	101.5	101.7	101.6	101.9	101.3	101.7	101.7	102.1	101.8	101.6	101.4	101.6	101.6	101.5	101.6	101.6
	Average Length (mm)	194.6	191.3	193.1	192.6	194.3	193.1	192.6	192.8	196.4	195.5	194.0	193.9	194.8	190.5	199.3	195.6
2	**Average Diameter (mm)**	101.7	101.6	101.8	102.0	101.2	101.4	101.5	101.8	101.5	101.7	101.4	101.8	101.1	101.9	101.5	101.7
	Average Length (mm)	195.4	193.6	194.8	191.5	192.2	192.7	195.1	193.0	194.8	196.1	194.0	194.8	195.3	193.8	198.5	195.4
3	**Average Diameter (mm)**	101.7	101.6	Not fabr.	102.1	Not fabr.	Not fabr.	Not fabr.	101.7	101.6	101.8	102.1	101.8	101.5	101.6	101.4	102.0
	Average Length (mm)	194.9	194.6	Not fabr.	194.0	Not fabr.	Not fabr.	Not fabr.	194.1	193.4	195.7	193.7	193.9	194.7	193.2	198.0	195.9

3.3.8. Concrete Mixture 8

Concrete for mixture 8 was sample was in St. Petersburg, FL on March 30, 2023. A picture of the construction site is shown in Figure 25. The mixture proportions are shown in Table 31. The concrete mixture was designed to meet FDOT class IV concrete with a minimum strength of 5500 psi. The fresh properties measured in the field are shown in Table 32. The curing temperatures recorded in the field during curing are shown in Figure 26.

Figure 25. Construction site 8 placement

Table 31. Concrete mix design information for mixture 8

Product	Quantity	Units
Cement Type IL	355	lb/yd^3
Slag	355	lb/yd^3
#57 Stone	1822	lb/yd^3
Silica Sand	1094	lb/yd^3
Air Entraining Admixture	0.1	fl oz/yd^3
Admixture for Concrete Type D Water - Reducing and Retarding I	28.4	fl oz/yd^3
Admixture for Concrete Type D Water - Reducing and Retarding II	28.4	fl oz/yd^3
Admixture for Concrete Type F Water - High Range Water Reducing	7.1	fl oz/yd^3
Water	292	lb/yd^3

Table 32. Field fresh properties construction site 8

Test	Sample 1	Sample 2
Slump (in)	5.0	4.75
Concrete temperature at placement (°F)	82	85
Unit Weight (lb/ft3)	147.9	149.9
Air Content, %	2.4%	2.0%

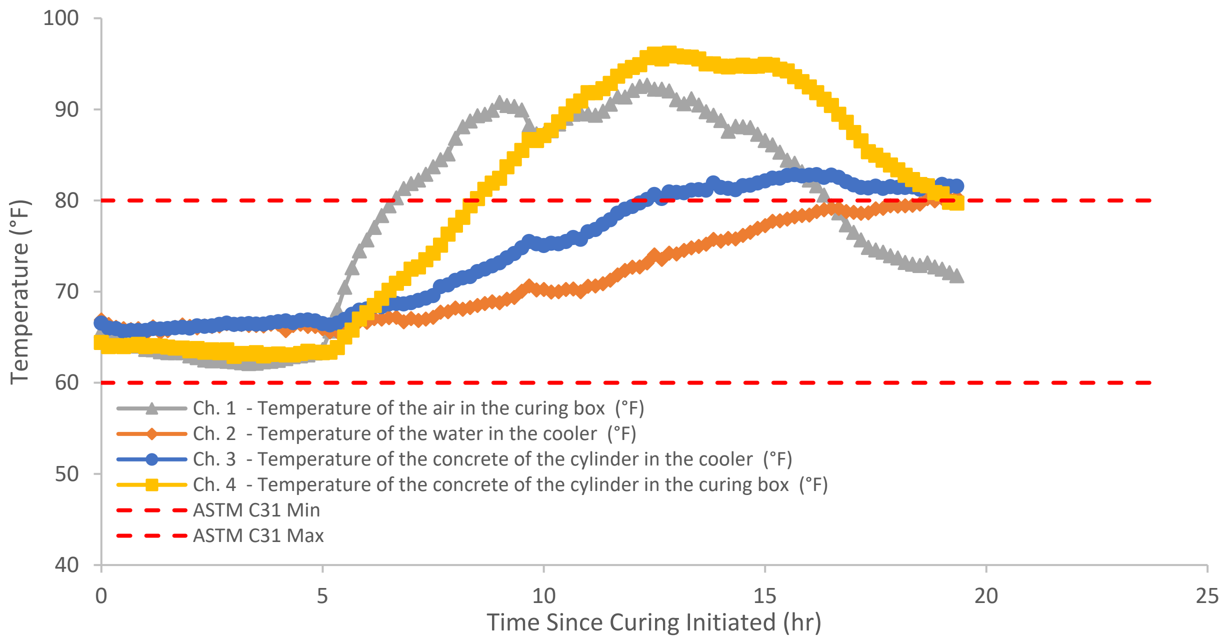

Figure 26. Curing temperatures measured for the field sampling for mixture 8

The concrete sampled in the field was reproduced under laboratory conditions with the materials collected from the ready-mixed concrete plant. The fresh properties measured from the reproduced mix in the laboratory are shown in Table 33. The curing temperatures recorded during curing for the laboratory-made concrete are shown in Figure 27. Specimen dimensions for the concrete cylinders made in the field and laboratory are shown in Table 34.

Table 33. Fresh properties measured in the laboratory for mixture 8

Test	**Batch1**	**Batch2**
Slump (in)	7.5	5.5
Concrete temperature at placement (°F)	74	74
Unit Weight (lb/ft^3)	148.7	149.5
Air Content, %	2.1%	1.6%

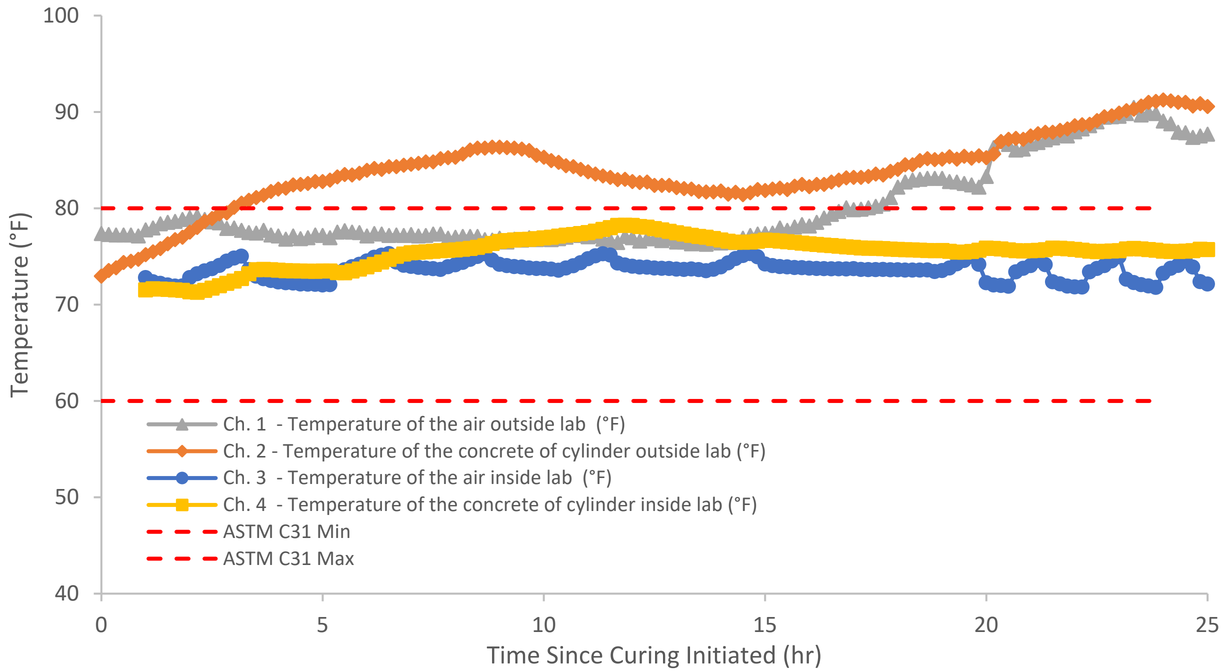

Figure 27. Temperatures measured during curing for samples made in the laboratory for mixture 8

Table 34. Specimen dimensions for concrete cylinders made for mixture 8

Cylinder		Determination															
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1	Average Diameter (mm)	101.8	101.3	101.6	101.5	101.8	101.7	101.6	101.6	101.7	101.9	101.6	101.8	101.6	101.5	101.5	101.5
	Average Length (mm)	196.0	194.4	198.4	194.8	196.8	198.1	198.2	195.1	193.6	193.5	197.8	196.1	195.1	197.9	198.7	195.1
2	Average Diameter (mm)	101.6	101.4	101.5	101.7	101.8	101.6	101.5	101.5	101.7	101.8	101.5	101.7	101.7	101.5	101.7	101.7
	Average Length (mm)	165.3	194.4	197.6	197.1	199.3	196.8	197.6	194.9	194.9	195.4	198.9	194.2	197.2	198.0	198.9	193.5
3	Average Diameter (mm)	101.7	101.8	not fabr	101.7	101.7	101.7	101.7	101.5	101.6	101.4	101.2	101.3	101.3	101.5	101.9	101.8
	Average Length (mm)	196.0	196.1	not fabr	195.1	196.8	195.8	198.1	197.8	195.5	192.7	199.5	195.8	197.2	197.4	198.8	196.6

3.3.9. Concrete Mixture 9

Concrete for mixture 9 was sampled from a construction site in Orlando, FL on June 2, 2023. The mixture proportions are shown in Table 35. The concrete mixture was designed to meet FDOT class II concrete with a minimum strength of 3400 psi. The fresh properties measured in the field are shown in Table 36. The temperatures recorded in the field during curing are shown in Figure 28.

Table 35. Concrete mix design information for mixture 9

Product	**Quantity**	**Units**
Cement Type IL	500	lb/yd^3
Fly Ash -Class F	125	lb/yd^3
#57 Stone	1650	lb/yd^3
Silica Sand	1250	lb/yd^3
Air Entraining Admixture	11.0	fl oz/yd^3
Admixture for Concrete Type D	43.8	fl oz/yd^3
Water	267	lb/yd^3

Table 36. Fresh properties measured in the field for mixture 9

Test	**Sample 1**	**Sample 2**
Slump (in)	5.0	2.5
Concrete temperature at placement (°F)	88	87
Unit Weight (lb/ft3)	138.2	137.4
Air Content, %	4.0%	4.2%

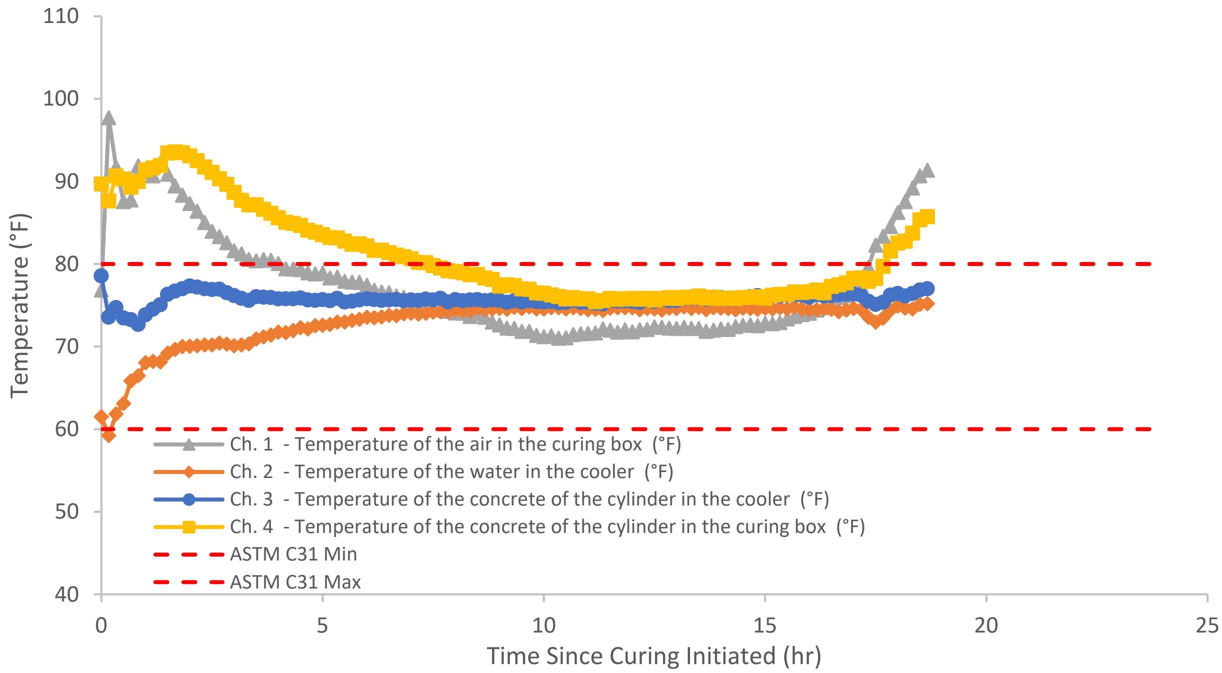

Figure 28. Curing temperatures measured for the field sampling for mixture 9

The concrete sampled in the field was reproduced under laboratory conditions with the materials collected from the ready-mixed concrete plant. The fresh properties measured from the reproduced mix in the laboratory are shown in Table 37. The curing temperatures recorded during curing for the laboratory-made concrete are shown in Figure 29. Specimen dimensions for the concrete cylinders made in the field and laboratory are shown in Table 38.

Table 37. Fresh properties measured in the laboratory for mixture 9

Test	**Batch 1**	**Batch 2**
Slump (in)	1.0	0.75
Concrete temperature at placement (°F)	75	73
Unit Weight (lb/ft^3)	142.0	142.4
Air Content, %	4.4%	4.5%

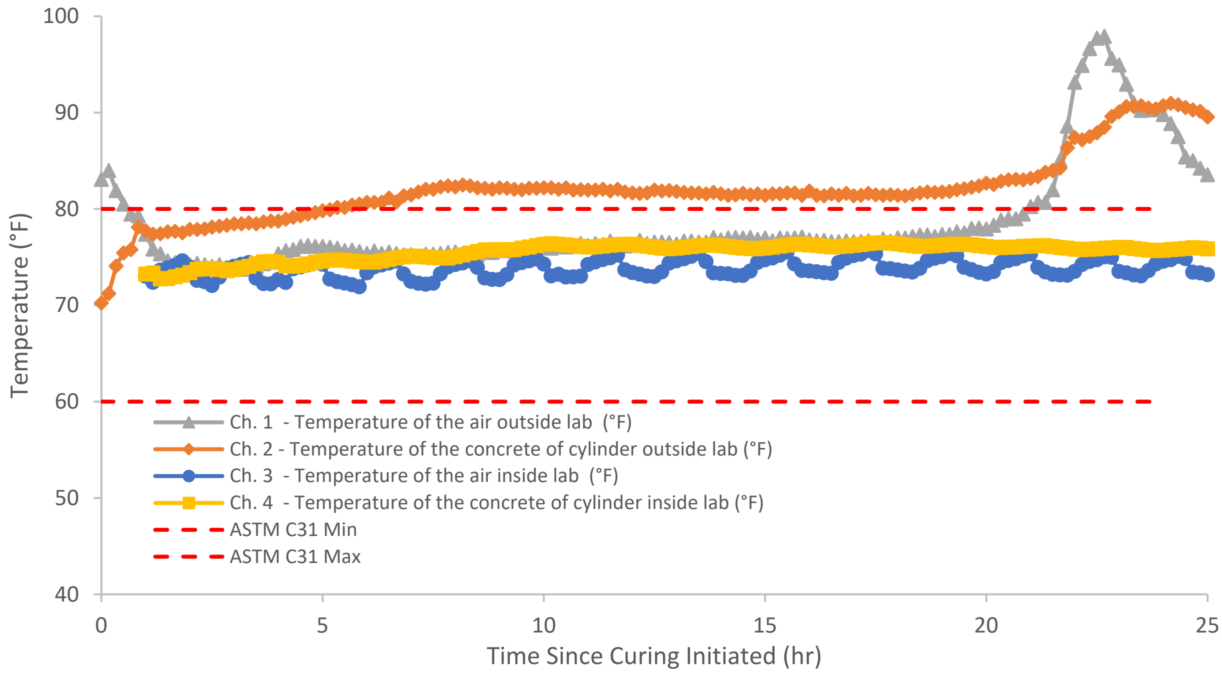

Figure 29. Temperatures measured during curing for samples made in the laboratory for mixture 9

Table 38. Specimen dimensions for concrete cylinders made for mixture 9

Cylinder		**Determination**															
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**
1	**Average Diameter (mm)**	101.5	101.6	101.8	101.4	101.7	101.3	101.9	101.4	101.6	101.4	101.6	101.4	101.4	101.9	102.5	101.5
	Average Length (mm)	199.3	198.2	195.6	199.7	194.6	195.1	164.8	199.0	196.7	200.0	194.2	198.2	196.8	196.9	198.4	198.4
2	**Average Diameter (mm)**	101.6	101.6	101.7	101.4	96.6	101.7	101.8	101.6	101.9	101.8	101.7	101.7	101.0	101.4	101.5	101.6
	Average Length (mm)	200.2	198.2	196.5	202.0	193.6	197.3	196.0	197.5	199.0	197.0	191.9	199.4	195.7	196.9	196.7	200.0
3	**Average Diameter (mm)**	101.3	101.6	101.7	101.4	96.8	101.1	101.9	101.7	101.7	101.7	101.3	101.5	101.1	101.0	101.3	101.5
	Average Length (mm)	200.3	197.2	196.0	197.5	197.5	196.4	196.1	200.3	197.6	196.9	195.6	198.2	196.0	196.3	195.8	198.2

3.3.10. Concrete Mixture 10

Concrete for mixture 10 was sampled from a construction site in Orlando, FL on June 16, 2023. The concrete mixture proportions are shown in Table 39. The concrete mixture was designed to meet FDOT Class IV concrete with a minimum strength of 5500 psi. The fresh properties measured in the field are shown in Table 40. The curing temperatures recorded in the field during curing are shown in Figure 30.

Table 39. Concrete mix design information for mixture 10

Product	**Quantity**	**Units**
Cement Type IL	375	lb/yd^3
Slag	375	lb/yd^3
#57 Stone	1642	lb/yd^3
Silica Sand	1013	lb/yd^3
Air Entraining Admixture	0.1	$fl\ oz/yd^3$
Admixture for Concrete Type D Water - Reducing and Retarding I	30.0	$fl\ oz/yd^3$
Admixture for Concrete Type D Water - Reducing and Retarding II	30.0	$fl\ oz/yd^3$
Water	308	lb/yd^3

Table 40. Fresh properties measured in the field for mixture 10

Test	**Sample 1**	**Sample 2**
Slump (in)	3.5	4.0
Concrete temperature at placement (°F)	91	90
Unit Weight (lb/ft3)	143.0	142.6
Air Content, %	2.6%	2.4%

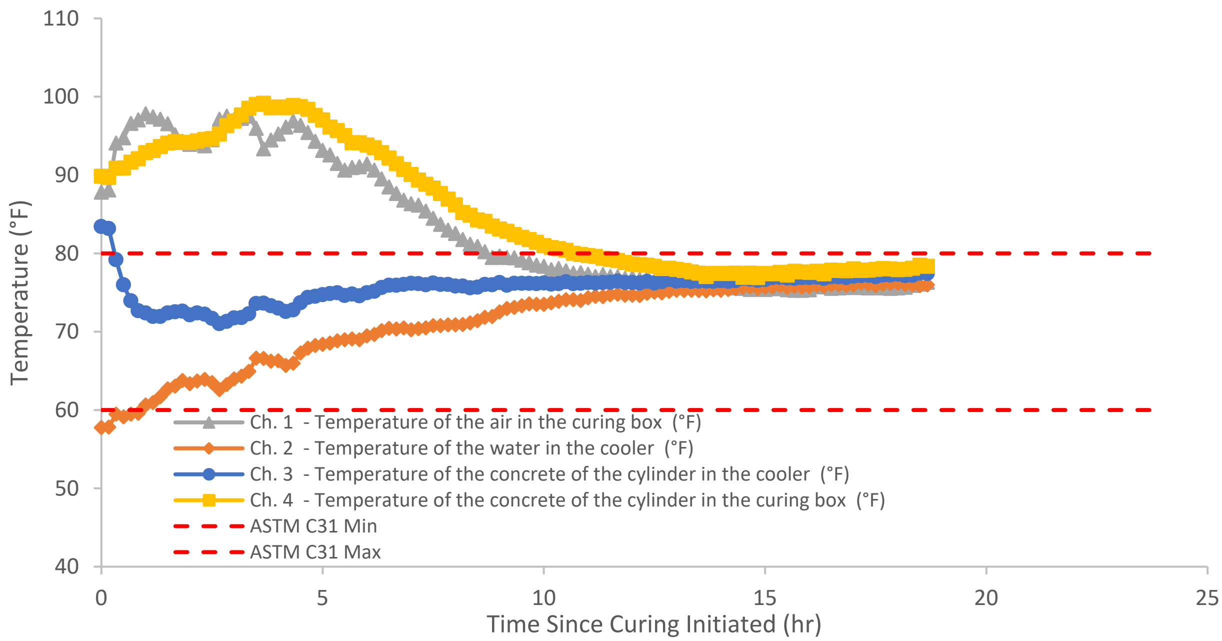

Figure 30. Curing temperatures measured for the field sampling for mixture 10

The concrete sampled in the field was reproduced under laboratory conditions with the materials collected from the ready-mixed concrete plant. The fresh properties measured from the reproduced mix in the laboratory are shown in Table 41. The temperatures recorded during curing for the laboratory-made concrete are shown in Figure 31. Specimen dimensions for the concrete cylinders made in the field and laboratory are shown in Table 42.

Table 41. Fresh properties measured in the laboratory for mixture 10

Test	**Batch 1**	**Batch 2**
Slump (in)	2.2	2.5
Concrete temperature at placement (°F)	75	74
Unit Weight (lb/ft^3)	145.2	145.5
Air Content, %	1.7%	1.2%

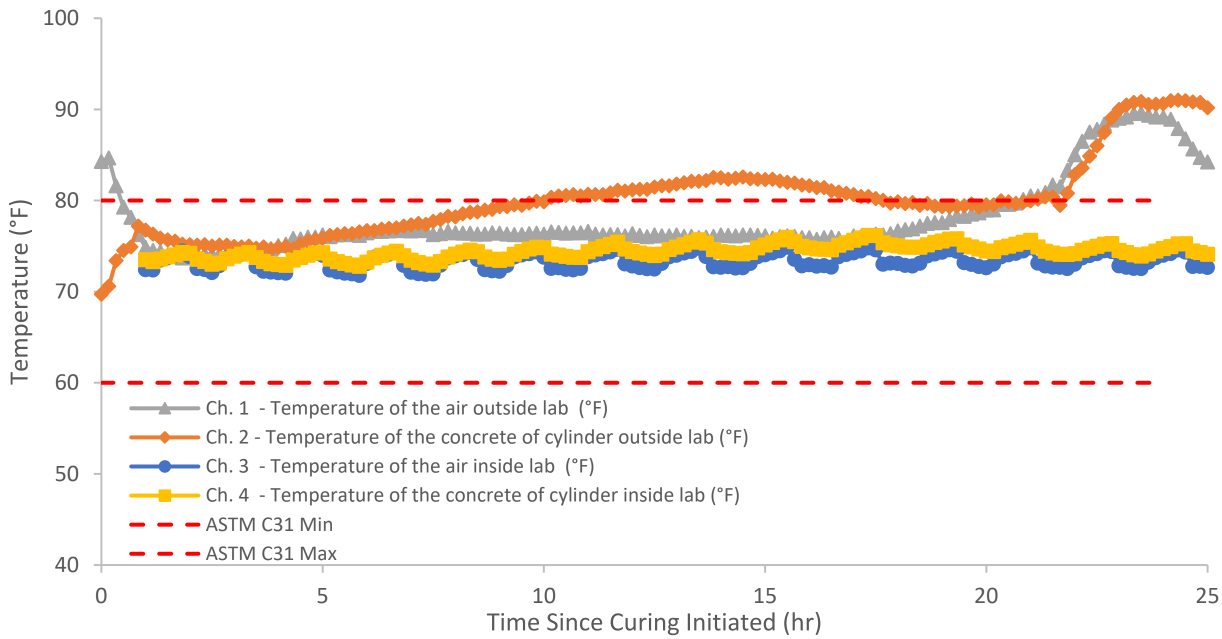

Figure 31. Curing temperatures measured for the field sampling for mixture 10

Table 42. Specimen dimensions for concrete cylinders made for mixture 10

Cylinder		Determination															
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**
1	**Average Diameter (mm)**	101.5	101.3	101.4	101.6	101.7	101.9	102.3	101.5	101.4	101.6	101.7	101.7	102.1	101.5	107.0	101.4
	Average Length (mm)	195.9	196.0	199.0	199.1	197.4	204.8	199.6	196.2	197.1	198.5	199.1	199.2	204.8	200.4	207.9	196.1
2	**Average Diameter (mm)**	101.5	101.4	101.4	101.7	101.8	101.9	101.7	101.6	101.6	101.7	not fabr	101.6	106.7	101.6	101.7	101.3
	Average Length (mm)	196.2	197.3	201.9	195.7	196.6	204.2	199.4	196.8	198.7	197.4	not fabr	197.1	204.0	201.5	201.4	197.4
3	**Average Diameter (mm)**	101.4	101.3	101.8	101.5	100.3	106.7	101.7	101.5	101.6	101.6	101.7	101.4	106.9	101.7	101.8	101.5
	Average Length (mm)	197.1	195.9	199.9	195.8	199.1	201.6	195.7	195.9	196.9	196.4	199.5	197.5	208.8	201.6	198.6	196.1

3.3.11. Concrete Mixture 11

Concrete for mixture 11 was sampled from a construction site in Miami, FL on June 20, 2023. The concrete mixture proportions are shown in Table 43. The concrete mixture was designed to meet FDOT Class IV concrete with a minimum strength of 5500 psi. The fresh properties measured in the field are shown in Table 44. The temperatures recorded in the field during curing are shown in Figure 32.

Table 43. Concrete mix design information for mixture 11

Product	**Quantity**	**Units**
Cement Type IL	360	lb/yd^3
Slag	360	lb/yd^3
#57 Stone	1630	lb/yd^3
Silica Sand	1174	lb/yd^3
Air Entraining Admixture	3.0	$fl\ oz/yd^3$
Admixture for Concrete Type D Water - Reducing and Retarding I	36.0	$fl\ oz/yd^3$
Admixture for Concrete Type D Water - Reducing and Retarding II	10.8	$fl\ oz/yd^3$
Admixture for Concrete Type S Water - Rheology Modifying	10.8	$fl\ oz/yd^3$
Water	267	lb/yd^3

Table 44. Fresh properties measured in the field for mixture 11

Test	**Sample 1**	**Sample 2**
Slump (in)	1.0	1.0
Concrete temperature at placement (°F)	85	90
Unit Weight (lb/ft^3)	145.9	147.1
Air Content, %	2.5%	3.0%

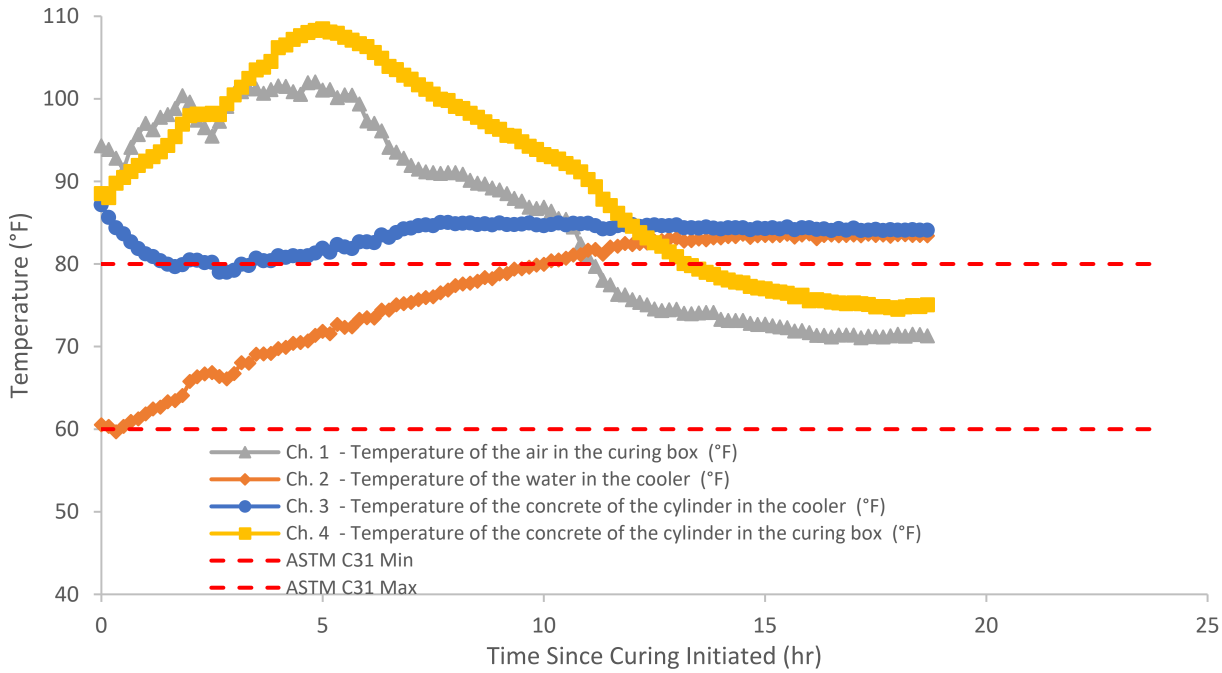

Figure 32. Curing temperatures measured for the field sampling for mixture 11

The concrete sampled in the field was reproduced under laboratory conditions with the materials collected from the ready-mixed concrete plant. The fresh properties measured from the reproduced mix in the laboratory are shown in Table 45. The temperatures recorded during curing for the laboratory-made concrete are shown in Figure 33. Specimen dimensions for the concrete cylinders made in the field and laboratory are shown in Table 46.

Table 45. Fresh properties measured in the laboratory for mixture 11

Test	Batch 1	Batch 2
Slump (in)	0.5	0.00
Concrete temperature at placement (°F)	80	76
Unit Weight (lb/ft^3)	145.9	44.9
Air Content, %	1.7%	2.1%

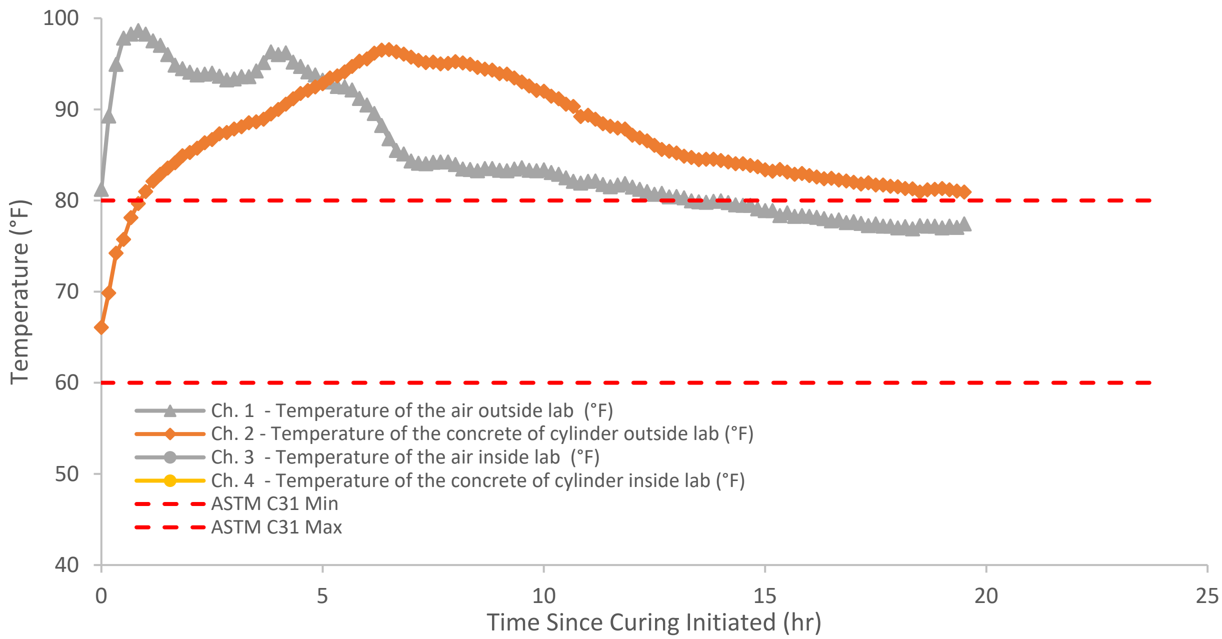

Figure 33. Temperatures measured during curing for samples made in the laboratory for mixture 11

Table 46. Specimen dimensions for concrete cylinders made for mixture 11

Cylinder		Determination															
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1	Average Diameter (mm)	101.4	101.4	101.3	101.6	101.8	101.8	101.6	101.5	101.7	101.8	101.8	101.4	101.7	101.4	101.8	101.4
	Average Length (mm)	193.0	185.9	198.7	199.9	200.9	200.4	198.7	197.3	199.4	196.7	200.5	196.5	198.9	200.0	199.5	195.9
2	Average Diameter (mm)	101.4	101.5	101.3	101.5	101.9	101.4	101.5	101.4	101.7	101.5	-	101.4	102.0	101.3	102.0	101.6
	Average Length (mm)	192.0	194.1	202.5	198.6	201.6	200.3	200.0	198.8	196.2	198.1	-	196.6	202.0	197.6	200.3	197.0
3	Average Diameter (mm)	101.7	101.5	101.2	101.6	102.2	101.5	101.6	101.5	101.9	101.8	101.6	101.5	101.7	101.4	102.3	101.8
	Average Length (mm)	193.3	192.4	201.5	196.8	198.2	201.1	202.2	196.4	198.0	196.7	201.4	197.2	198.1	202.1	199.6	196.9

3.3.12. Concrete Mixture 12

Concrete was sampled for mixture 12 at a construction site in Orlando, FL on June 28, 2023. The mixture proportions are shown in Table 47. The concrete mixture was designed to meet FDOT Class II concrete requirements with a minimum strength of 3400 psi. The fresh properties measured in the field are shown in Table 48. The temperatures recorded in the field during curing are shown in Figure 34.

Table 47. Concrete mix design information for mixture 12

Product	**Quantity**	**Units**
Cement Type IL	232	lb/yd^3
Slag	243	lb/yd^3
#57 Stone	1755	lb/yd^3
Silica Sand	1351	lb/yd^3
Air Entraining Admixture	0.1	$fl\ oz/yd^3$
Admixture for Concrete Type D Water - Reducing and Retarding I	57.0	$fl\ oz/yd^3$
Water	250	lb/yd^3

Table 48. Fresh properties measured in the field for mixture 12

Test	**Sample 1**	**Sample 2**
Slump (in)	2.75	2.5
Concrete temperature at placement (°F)	78	77
Unit Weight (lb/ft3)	143.8	145.0
Air Content, %	2.5%	1.8%

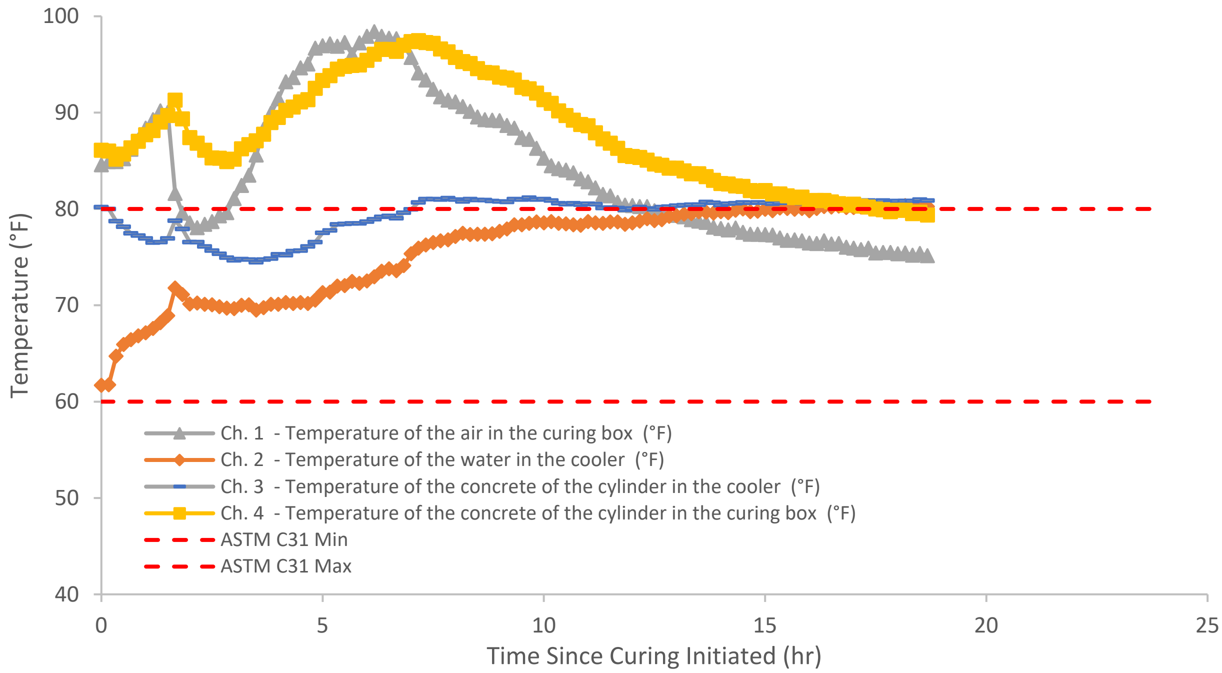

Figure 34. Curing temperatures measured for the field sampling for mixture 12

The concrete sampled in the field was reproduced under laboratory conditions with the materials collected from the ready-mixed concrete plant. The fresh properties measured from the reproduced mix in the laboratory are shown in Table 49. The curing temperatures recorded during curing for the laboratory-made concrete are shown in Figure 35. Specimen dimensions for the concrete cylinders made in the field and laboratory are shown in Table 50.

Table 49. Fresh properties measured in the laboratory for mixture 12

Test	**Batch 1**	**Batch 2**
Slump (in)	2.0	1.0
Concrete temperature at placement (°F)	74	75
Unit Weight (lb/ft^3)	143.8	145.7
Air Content, %	3.0%	2.0%

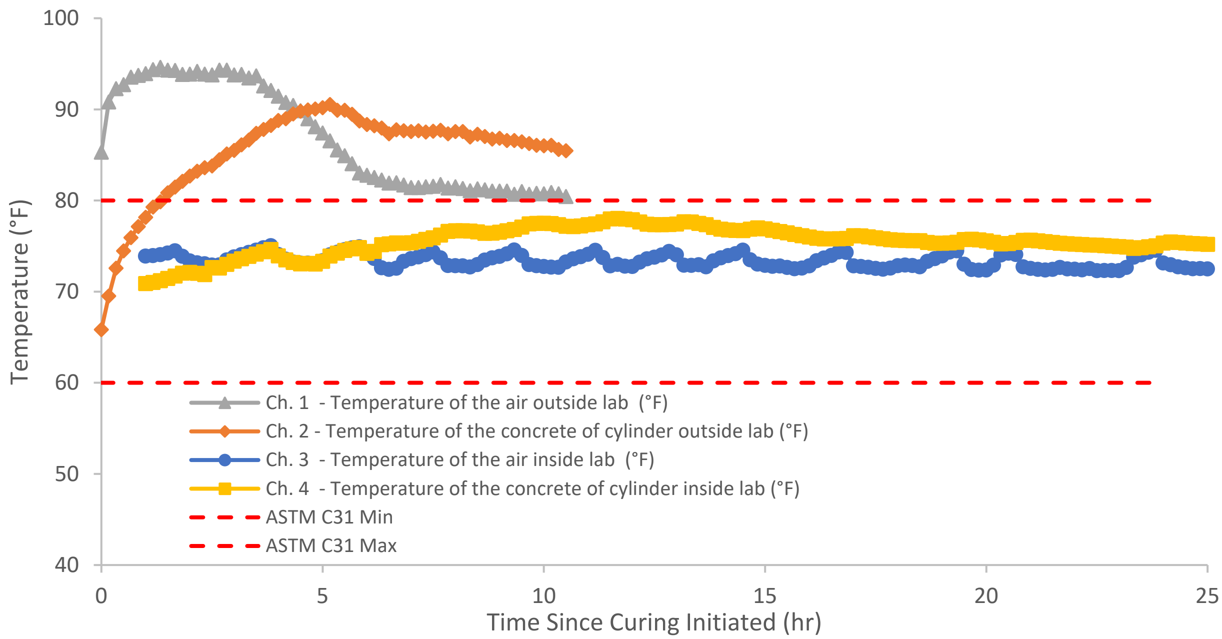

Figure 35. Temperatures measured during curing for samples made in the laboratory for mixture 12

Table 50. Specimen dimensions for concrete cylinders made for mixture 12

Cylinder		Determination															
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1	Average Diameter (mm)	101.5	101.7	101.2	101.5	101.7	101.2	101.4	101.4	101.5	101.3	101.5	101.5	101.8	101.5	101.4	101.3
	Average Length (mm)	195.2	195.2	198.4	194.2	201.5	198.4	198.0	198.1	199.2	195.2	197.9	194.3	200.2	199.4	197.5	195.7
2	Average Diameter (mm)	102.0	101.7	101.2	101.6	101.9	101.2	101.4	101.5	101.6	101.3	101.4	101.6	101.7	101.9	101.7	101.3
	Average Length (mm)	195.5	194.4	199.8	194.4	199.5	199.8	197.1	195.6	197.6	196.8	198.2	197.0	198.7	200.0	196.7	196.6
3	Average Diameter (mm)	405.3	101.5	101.2	101.7	101.6	101.2	101.6	101.4	101.7	101.4	101.8	101.6	101.8	101.7	101.7	101.5
	Average Length (mm)	195.1	195.0	198.8	201.0	200.6	198.8	200.3	194.7	199.9	197.1	196.9	196.1	199.8	201.5	200.5	196.3

3.3.13. Concrete Mixture 13

Concrete was sampled for mixture 13 from a construction site in Miami, FL on July 6, 2023. The concrete mixture proportions are shown in Table 51. The concrete mixture was designed to meet FDOT class IV concrete with a minimum strength of 5500 psi. The concrete fresh properties measured in the field are shown in Table 52. The temperatures recorded in the field during curing are shown in Figure 36.

Table 51. Concrete mix design information for mixture 13

Product	**Quantity**	**Units**
Cement Type IL	502	lb/yd^3
Slag	168	lb/yd^3
#57 Stone	1630	lb/yd^3
Silica Sand	1154	lb/yd^3
Air Entraining Admixture	2.5	$fl\ oz/yd^3$
Admixture for Concrete Type D Water - Reducing and Retarding I	33.5	$fl\ oz/yd^3$
Admixture for Concrete Type D Water - Reducing and Retarding II	10.0	$fl\ oz/yd^3$
Water	275	lb/yd^3

Table 52. Fresh properties measured in the field for mixture 13

Test	**Sample 1**	**Sample 2**
Slump (in)	2.5	3.5
Concrete temperature at placement (°F)	90	91
Unit Weight (lb/ft3)	146.3	143.8
Air Content, %	1.5%	2.0%

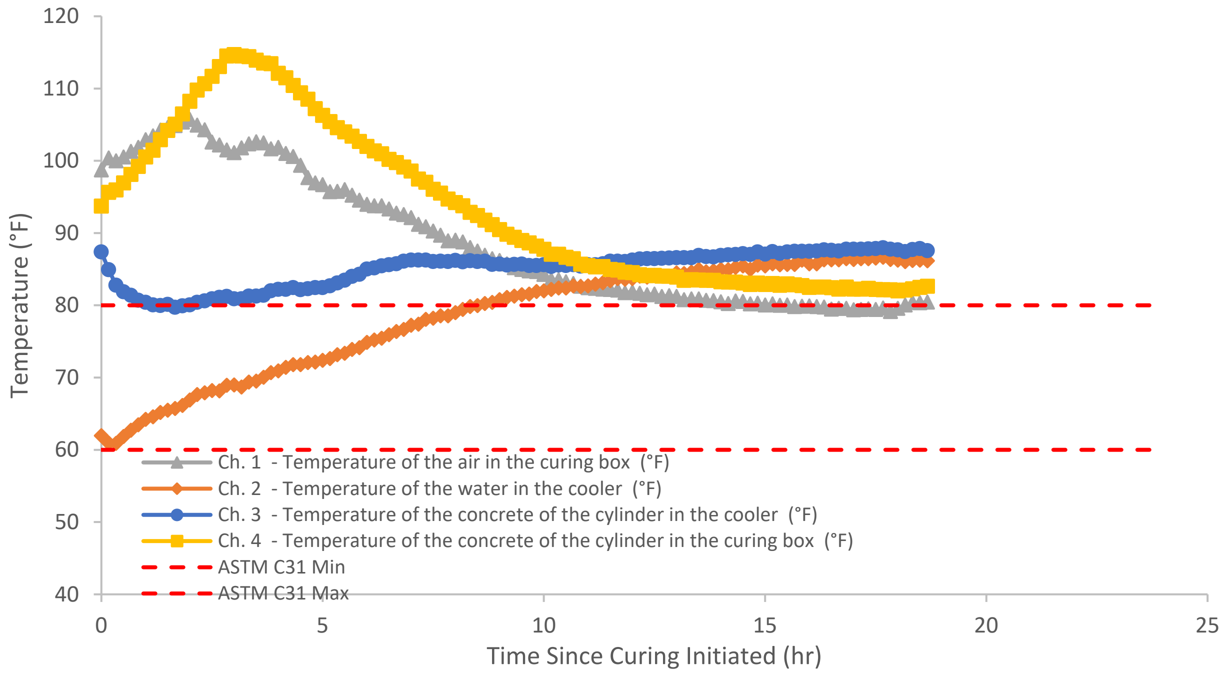

Figure 36. Curing temperatures measured for the field sampling for mixture 13

The concrete sampled in the field was reproduced under laboratory conditions with the materials collected from the ready-mixed concrete plant. The fresh properties measured from the reproduced concrete in the laboratory are shown in Table 53. The temperatures recorded during curing for the laboratory-made concrete are shown in Figure 37. Specimen dimensions for the concrete cylinders made in the field and laboratory are shown in Table 54.

Table 53. Laboratory fresh properties construction site 13

Test	**Batch 1**	**Batch 2**
Slump (in)	2.0	2.5
Concrete temperature at placement (°F)	74	74
Unit Weight (lb/ft^3)	136.2	141.4
Air Content, %	1.9%	1.7%

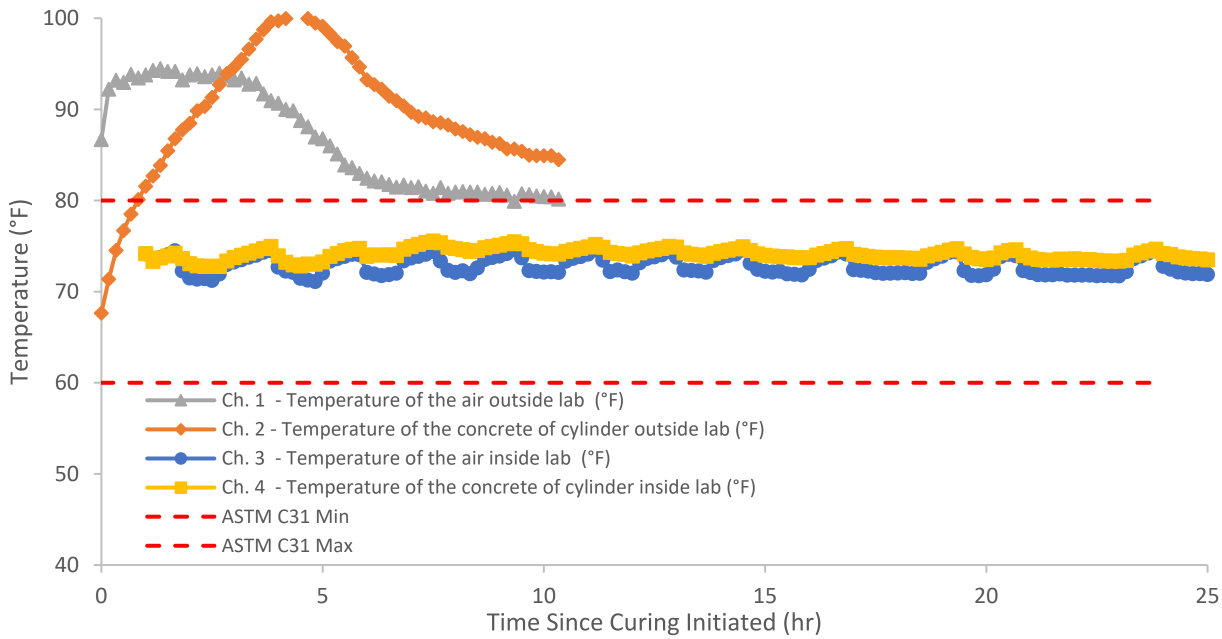

Figure 37. Temperatures measured during curing for samples made in the laboratory for mixture 13

Table 54. Specimen dimensions for concrete cylinders made for mixture 13

Cylinder		Determination															
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**
1	**Average Diameter (mm)**	101.3	101.6	101.8	101.8	101.5	101.5	101.8	101.5	101.8	101.7	117.2	101.7	101.9	101.7	101.8	101.8
	Average Length (mm)	200.8	200.0	202.6	199.1	198.3	199.1	196.9	201.8	200.0	198.1	212.2	196.2	202.2	199.1	196.0	198.6
2	**Average Diameter (mm)**	101.5	101.6	111.2	101.6	101.9	101.6	111.9	100.6	102.1	101.8	101.6	102.0	107.1	106.8	101.4	101.6
	Average Length (mm)	201.0	199.1	213.2	200.8	197.9	198.2	198.3	196.7	200.4	195.6	195.6	199.4	201.2	206.1	198.4	198.1
3	**Average Diameter (mm)**	101.7	101.2	116.8	101.6	102.0	101.6	101.7	101.7	101.7	101.7	101.7	101.6	107.3	112.1	101.5	101.7
	Average Length (mm)	200.2	198.5	214.4	198.4	198.8	200.8	198.3	201.7	198.7	196.6	168.5	201.0	202.8	206.7	196.8	195.2

3.3.14. Concrete Mixture 14

Concrete for mixture 14 was sampled from a construction site in Tampa, FL on July 21, 2023. The concrete mixture proportions are shown in Table 55. The concrete mixture was designed to meet FDOT class IV concrete with a minimum strength of 5500 psi. The fresh properties measured in the field are shown in Table 56. The temperatures recorded in the field during curing are shown in Figure 38.

Table 55. Concrete mix design information for mixture 14

Product	**Quantity**	**Units**
Cement Type IL	266	lb/yd^3
Slag	399	lb/yd^3
Metakaolin	60	lb/yd^3
#57 Stone	1714	lb/yd^3
Silica Sand	1142	lb/yd^3
Air Entraining Admixture	0.1	$fl\ oz/yd^3$
Admixture for Concrete Type A Water - Reducing I	58.0	$fl\ oz/yd^3$
Admixture for Concrete Type A Water - Reducing II	30.5	$fl\ oz/yd^3$
Water	254	lb/yd^3

Table 56. Field fresh properties construction site 14

Test	**Sample 1**	**Sample 2**
Slump (in)	8.5	8.5
Concrete temperature at placement (°F)	90	90
Unit Weight (lb/ft3)	143.4	147.5
Air Content, %	1.8%	1.2%

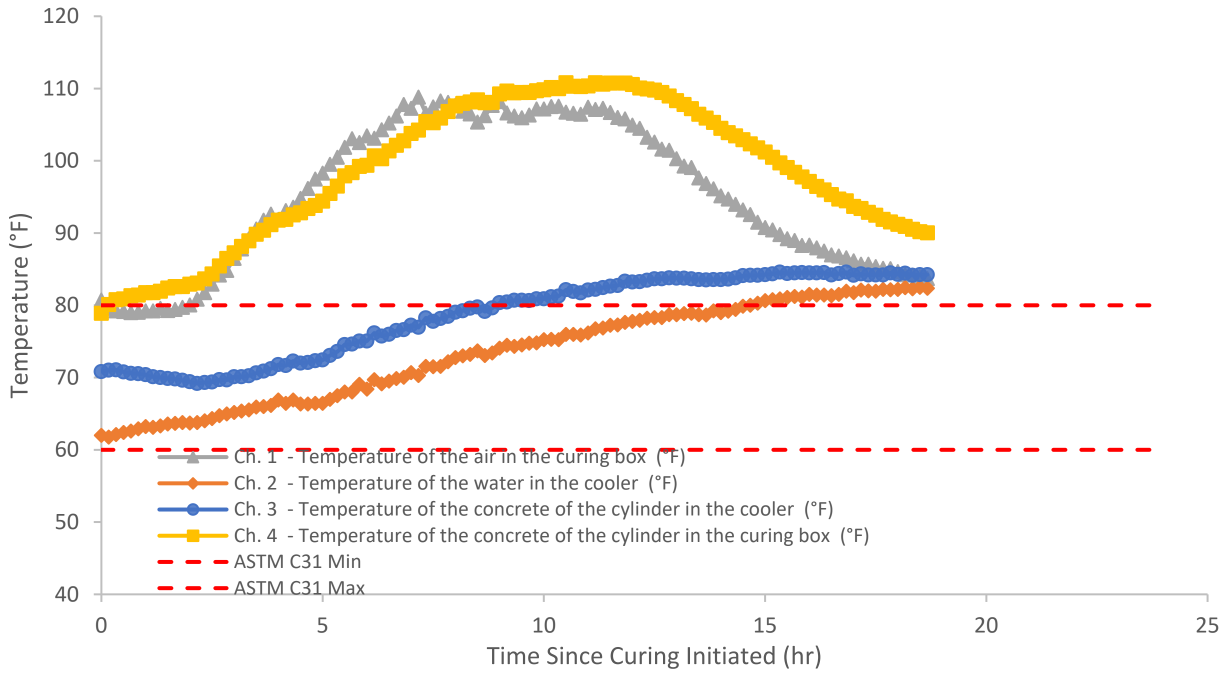

Figure 38. Curing temperatures measured for the field sampling for mixture 14

The concrete sampled in the field was reproduced under laboratory conditions with materials collected from the ready-mixed concrete plant. The fresh properties measured from the reproduced concrete in the laboratory are shown in Table 57. The temperatures recorded during curing for the laboratory-made concrete are shown in Figure 39. Specimen dimensions for the concrete cylinders made in the field and laboratory are shown in Table 58.

Table 57. Fresh properties measured in the laboratory for mixture 14

Test	**Batch 1**	**Batch 2**
Slump (in)	9.5	9.5
Concrete temperature at placement (°F)	74	76
Unit Weight (lb/ft^3)	144.6	146.3
Air Content, %	0.3%	0.3%

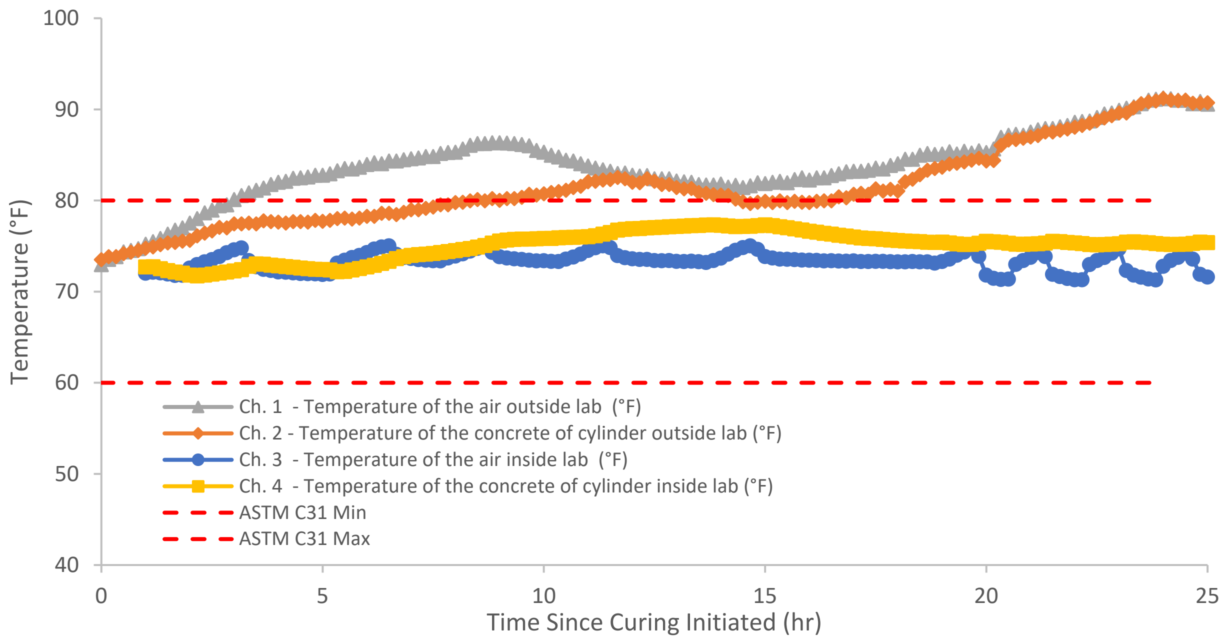

Figure 39. Temperatures measured during curing for samples made in the laboratory for mixture 14

Table 58. Specimen dimensions for concrete cylinders made for mixture 14

Cylinder		Determination															
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**
1	**Average Diameter (mm)**	101.5	101.7	101.7	101.8	101.2	101.8	101.8	101.6	101.8	101.2	101.3	101.7	101.5	101.3	101.6	101.6
	Average Length (mm)	196.6	193.4	199.8	190.4	197.2	198.2	198.2	194.8	134.0	193.2	196.5	192.0	196.5	199.4	195.1	191.3
2	**Average Diameter (mm)**	101.7	101.6	101.5	101.7	101.4	101.9	101.9	101.6	101.6	101.8	101.4	101.6	101.7	101.5	101.5	101.7
	Average Length (mm)	194.2	191.8	197.3	194.1	196.8	199.8	199.8	195.5	165.0	194.4	196.5	191.4	197.5	195.6	196.5	194.3
3	**Average Diameter (mm)**	101.5	101.4	101.3	101.4	101.6	101.9	101.9	101.6	101.5	101.6	101.3	101.7	101.4	101.9	101.5	102.1
	Average Length (mm)	194.7	191.0	196.8	192.9	197.8	196.3	196.3	196.2	196.4	194.8	195.4	195.4	164.3	196.2	194.5	193.5

3.3.15. Concrete Mixture 15

Concrete was sampled for mixture 15 from a construction site in Miami, FL on August 9, 2023. The concrete mixture proportions are shown in Table 59. The concrete mixture was designed to meet FDOT class II concrete with a minimum strength of 3400 psi. The fresh properties measured in the field are shown in Table 60. The temperatures recorded in the field during curing are shown in Figure 40.

Table 59. Concrete mix design information for mixture 15

Product	**Quantity**	**Units**
Cement Type IL	500	lb/yd^3
Fly Ash -Class F	125	lb/yd^3
#57 Stone	1650	lb/yd^3
Silica Sand	1260	lb/yd^3
Air Entraining Admixture	11.0	$fl\ oz/yd^3$
Admixture for Concrete Type D Water - Reducing and Retarding I	43.8	$fl\ oz/yd^3$
Water	267	lb/yd^3

Table 60. Field fresh properties construction site 15

Test	**Sample 1**	**Sample 2**
Slump (in)	3.0	2.5
Concrete temperature at placement (°F)	90	90
Unit Weight (lb/ft3)	144.6	143.0
Air Content, %	2.5%	2.1%

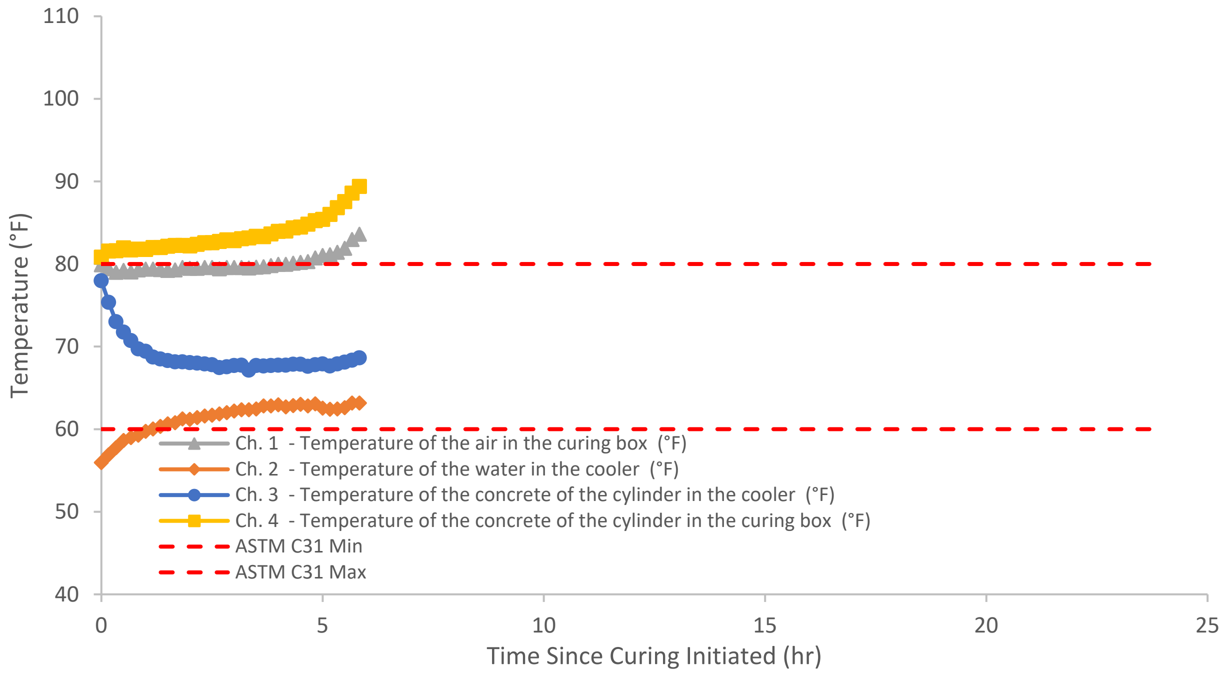

Figure 40. Curing temperatures measured for the field sampling for mixture 15

The concrete sampled in the field was reproduced under laboratory conditions with the materials collected from the ready-mixed concrete plant. The fresh properties measured from the reproduced concrete in the laboratory are shown in Table 61 The curing temperatures recorded during curing for the laboratory-made concrete are shown in Figure 41. Specimen dimensions for the concrete cylinders made in the field and laboratory are shown in Table 62.

Table 61. Fresh properties measured in the laboratory for mixture 15

Test	**Batch 1**	**Batch 2**
Slump (in)	2.75	2.75
Concrete temperature at placement (°F)	74	75
Unit Weight (lb/ft^3)	140.6	141.4
Air Content, %	4.6%	5.2%

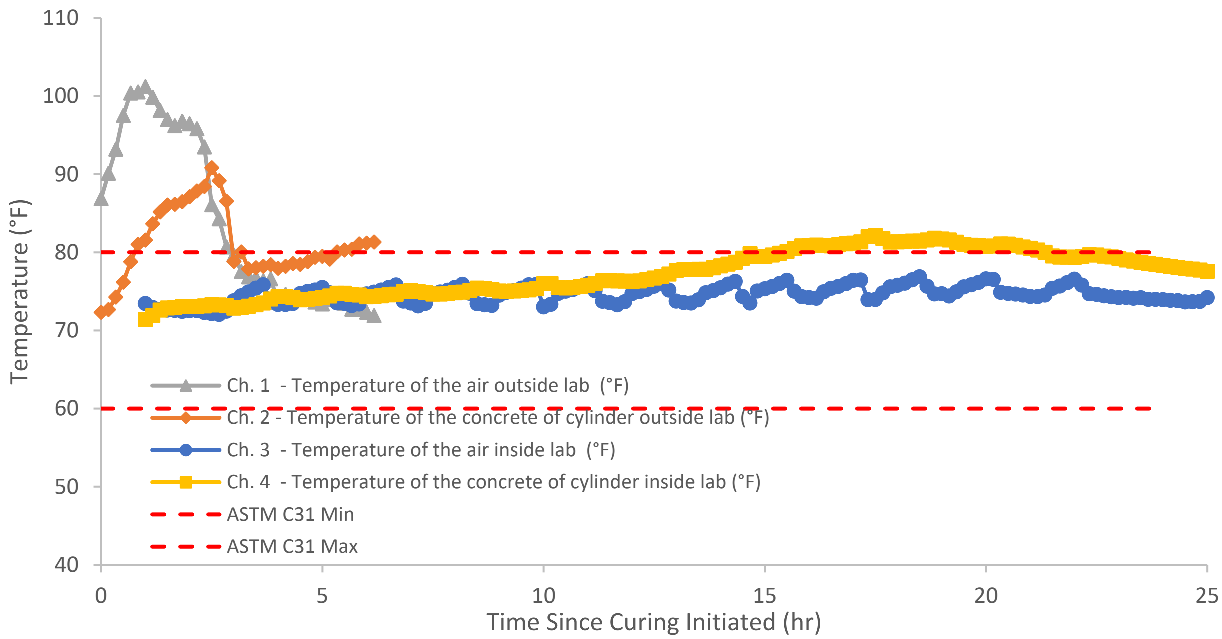

Figure 41. Temperatures measured during curing for samples made in the laboratory for mixture 15

Table 62. Specimen dimensions for concrete cylinders made for mixture 15

Cylinder		Determination															
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1	Average Diameter (mm)	101.6	101.6	101.9	101.7	101.5	101.8	101.7	101.4	101.8	101.5	101.5	101.9	101.7	101.6	101.9	101.5
	Average Length (mm)	193.4	193.6	196.8	196.4	198.3	195.7	194.1	194.1	194.7	192.9	194.7	194.6	195.5	197.1	196.4	195.9
2	Average Diameter (mm)	101.6	101.6	101.8	101.5	101.7	101.5	101.7	101.5	101.6	101.5	101.5	101.7	101.6	101.4	101.8	101.6
	Average Length (mm)	192.9	195.3	194.9	192.7	198.9	198.4	193.0	194.7	194.8	190.8	195.0	195.1	195.9	195.3	196.2	193.4
3	Average Diameter (mm)	101.8	101.8	101.6	101.6	101.6	101.4	101.8	101.8	101.8	101.5	101.6	101.9	101.5	101.6	101.6	101.7
	Average Length (mm)	192.8	193.5	198.9	194.4	195.9	196.4	194.0	194.1	194.1	194.8	197.0	200.4	196.8	195.0	194.3	193.5

3.4. Summary

Concrete specimens were made for 15 construction mixture designs in the field at construction sites in Florida to study any differences in concrete resistivity between samples made in the field and laboratory. Materials used for the selected placements were collected from the same ready-mix plants used to produce the field concrete and were used to reproduce the mix designs under laboratory conditions. Concrete fresh properties were measured for all concrete mixtures sampled and specimens were subjected to two different initial curing methods for measurement of the 28-, 56-, and 91-day concrete surface and bulk resistivity.

4. RUGGEDNESS STUDY

Concrete electrical resistivity tests are used to measure the long-term durability of concrete mixtures due to its ease, speed of testing, and good correlation with other tests to concrete permeability [2]. A ruggedness study following ASTM C1067 [82] and ASTM E1169 [7] was performed to determine the influence of identified potential factors in the variability of surface and bulk resistivity methods.

4.1. Methods

4.1.1. Resistivity Testing

AASHTO T 358 [36] and AASHTO TP 119 [24] were used to measure the concrete surface and bulk resistivity, respectively. Three different apparatus were used to measure the concrete resistivity: the Giatec Surf™ to measure the surface resistivity, the Giatec RCON™ to measure bulk resistivity, and the Proceq Resipod to measure surface resistivity and bulk resistivity when used with stainless steel plates connected to the electrodes. The specimens were rinsed with tap water before measuring the resistivity. The specimen surface resistivity was measured with the Surf™ using the ASTM mode on the equipment. Then the specimen was tested for surface resistivity using the custom mode with the frequency described in the testing matrix. The frequency of testing of the equipment was only possible to set with the Giatec equipment. The specimen was tested for surface resistivity with the Proceq Resipod, maintaining the moisture of the specimen. The specimen bulk resistivity was then measured with the RCON™ and Proceq Resipod using the connected stainless steel end plates. The temperature was measured at every step with a laser thermometer. The resistivity test setup can be seen in Figure 42. Figure 43 shows the frequency setup option for the Surf™. Figure 44 shows the frequency setup option for the RCON™.

Figure 42. Resistivity testing setup

Figure 43. Frequency setup for SURF^{TM}

Figure 44. Frequency setup RCON^{TM}

Individual limewater tanks and communal limewater tanks were conditioned as per ASTM C511 [62]. A communal limewater tank can be seen in Figure 45.

Figure 45. Communal limewater tank

4.1.2. Material Characterization

Coarse aggregate gradations were measured according to ASTM C136 [83], while their absorption and specific gravity were measured according to ASTM C127 [84]. Fine aggregate gradations were measured according to ASTM C136 [83], while their absorption and specific gravity were measured according to ASTM C128 [85].

4.1.3. Ruggedness Study Implementation

Table 63 shows the concrete resistivity factors studied and their levels based on ASTM C1067 [82] level assignation for the ruggedness test. Table 64 shows the matrix pattern of signs constructed for the factors following ASTM C1067 [82], modified to study 6 factors as directed by ASTM E1169 [7]. Table 65 shows the sign matrix that was used to perform the ruggedness calculations adapted from ASTM C1067 [82] with the proposed experimental matrix of 6 factors and 16 determinations studied.

Table 63. Levels tested for factors studied

Factor		Levels	
		-	+
A	Frequency	100	40
B	Temperature control	Cooler w tempered water	Uninsulated box
C	Time of demolding	7 days	24-48 hrs
D	Limewater	Communal	Individual
E	Sample moisture state during testing	Dry	Wet
F	Sample production	Lab	Field

Table 64. Pattern of sign matrix

Factor	Determination number							
	1	2	3	4	5	6	7	8
A - Frequency	1	-1	-1	1	-1	1	1	-1
B - Temperature control	1	1	-1	-1	1	-1	1	-1
C - Time of demolding	1	1	1	-1	-1	1	-1	-1
D - Limewater	-1	1	1	1	-1	-1	1	-1
F - Sample moisture state during testing	-1	1	-1	1	1	1	-1	-1
G - Sample production	-1	-1	1	-1	1	1	1	-1

Table 65. Matrix of signs

Row	Eight determinations for Replicate Set 1								Eight determinations for Replicate Set 2							
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
2	1	-1	-1	1	-1	1	1	-1	1	-1	-1	1	-1	1	1	-1
3	1	1	-1	-1	1	-1	1	-1	1	1	-1	-1	1	-1	1	-1
4	1	1	1	-1	-1	1	-1	-1	1	1	1	-1	-1	1	-1	-1
5	-1	1	1	1	-1	-1	1	-1	-1	1	1	1	-1	-1	1	-1
6	-1	1	-1	1	1	1	-1	-1	-1	1	-1	1	1	1	-1	-1
7	-1	-1	1	-1	1	1	1	-1	-1	-1	1	-1	1	1	1	-1
8	1	1	1	1	1	1	1	1	-1	-1	-1	-1	-1	-1	-1	-1
9	1	-1	-1	1	-1	1	1	-1	-1	1	1	-1	1	-1	-1	1
10	1	1	-1	-1	1	-1	1	-1	-1	-1	1	1	-1	1	-1	1
11	1	1	1	-1	-1	1	-1	-1	-1	-1	-1	1	1	-1	1	1
12	-1	1	1	1	-1	-1	1	-1	1	-1	-1	-1	1	1	-1	1
13	-1	1	-1	1	1	1	-1	-1	1	-1	1	-1	-1	-1	1	1
14	-1	-1	1	-1	1	1	1	-1	1	1	-1	1	-1	-1	-1	1

4.2. Results

4.2.1. Aggregate Characterization

Table 66 shows the specific gravity measured for the coarse and fine aggregates, while Table 67 shows the absorption capacity measured for the coarse and fine aggregates. The coarse aggregate gradations measured are shown from Figure 46 to Figure 60, while the fine aggregate gradations measured are shown from Figure 61 to Figure 75.

Table 66. Aggregate specific gravities

Mix	Coarse Aggregate I	Coarse Aggregate II	Fine Aggregate I
1	2.35	n/a	2.66
2	2.35	n/a	2.66
3	2.49	n/a	2.64
4	2.49	n/a	2.64
5	2.45	n/a	2.64
6	2.45	n/a	2.64
7	2.46	n/a	2.66
8	2.69	n/a	2.65
9	2.38	2.41	2.64
10	2.38	n/a	2.64
11	2.36	n/a	2.65
12	2.48	n/a	2.64
13	2.38	n/a	2.65
14	2.45	n/a	2.64
15	2.48	n/a	2.64

Table 67. Aggregate absorption capacities

Mix	Coarse Aggregate I (%)	Coarse Aggregate II (%)	Fine Aggregate I (%)
1	6.53	n/a	0.4
2	6.53	n/a	0.4
3	5.1	n/a	0.2
4	5.1	n/a	0.2
5	6.4	n/a	0.3
6	6.4	n/a	0.3
7	6.27	n/a	0.4
8	1.18	n/a	0.32
9	4.15	4.58	0.1

10	4.15	n/a	0.1
11	4.28	n/a	0.08
12	5.5	n/a	0.2
13	4.15	n/a	0.08
14	6.4	n/a	0.3
15	2.6	n/a	0.2

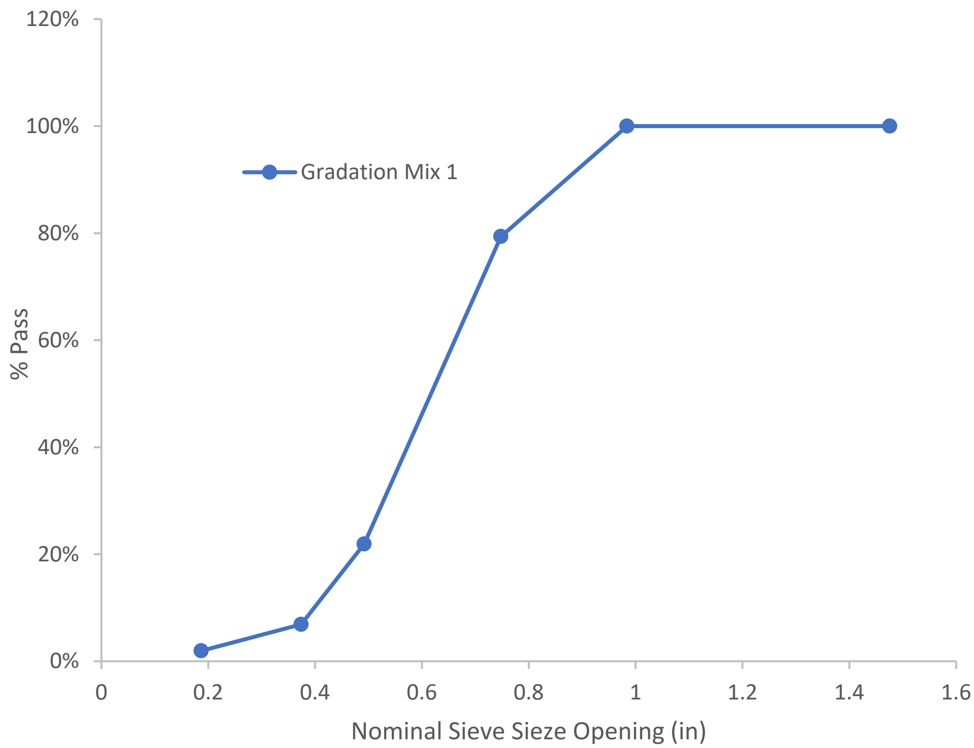

Figure 46. Mix 1 coarse aggregate gradation

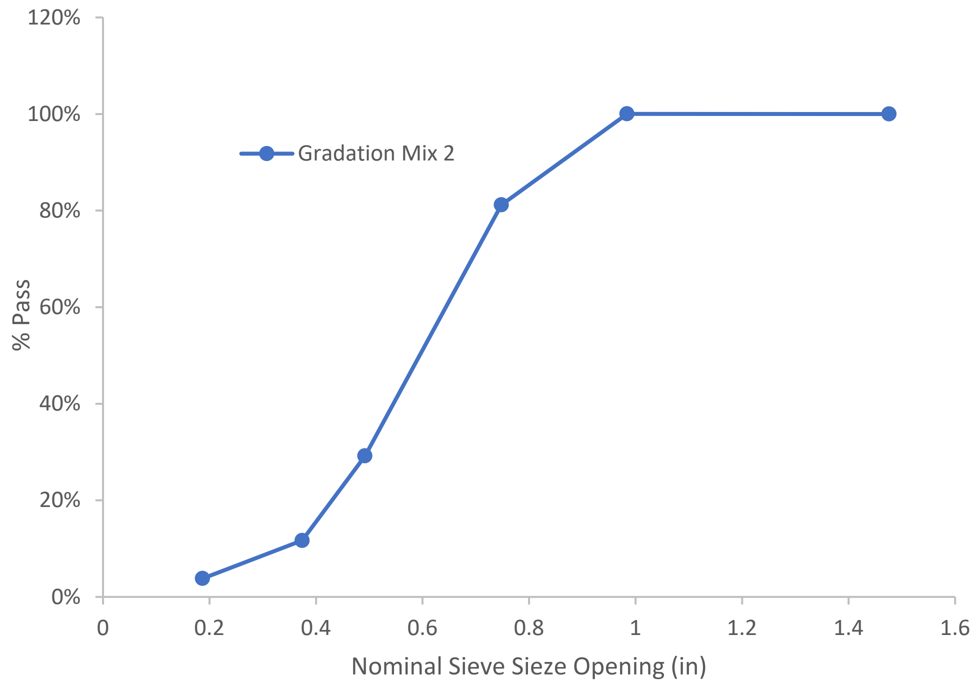

Figure 47. Mix 2 coarse aggregate gradation

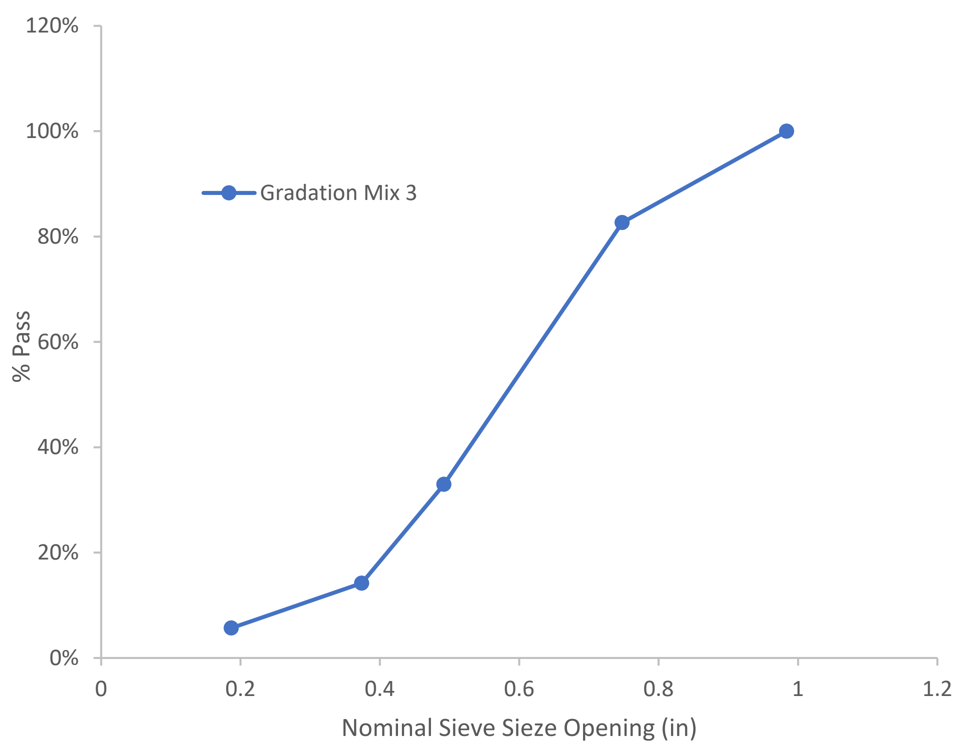

Figure 48. Mix 3 coarse aggregate gradation

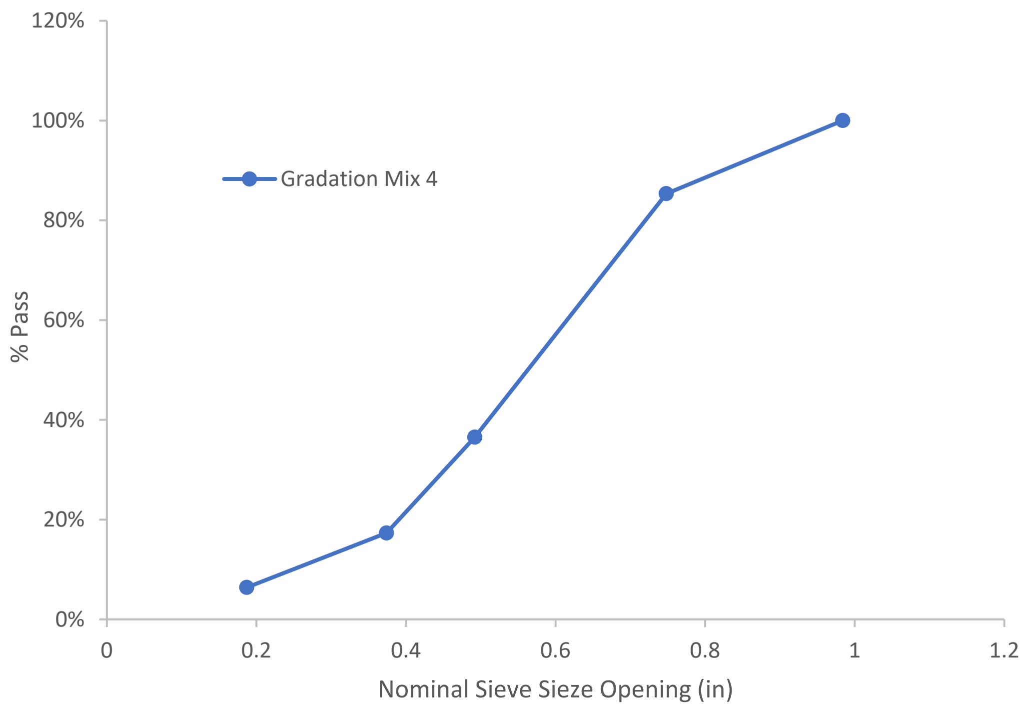

Figure 49. Mix 4 coarse aggregate gradation

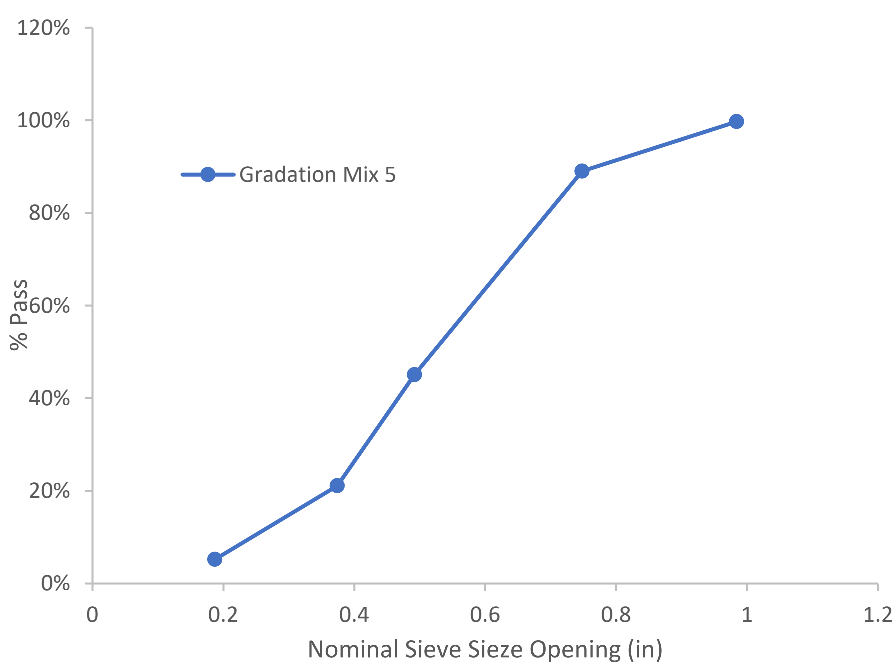

Figure 50. Mix 5 coarse aggregate gradation

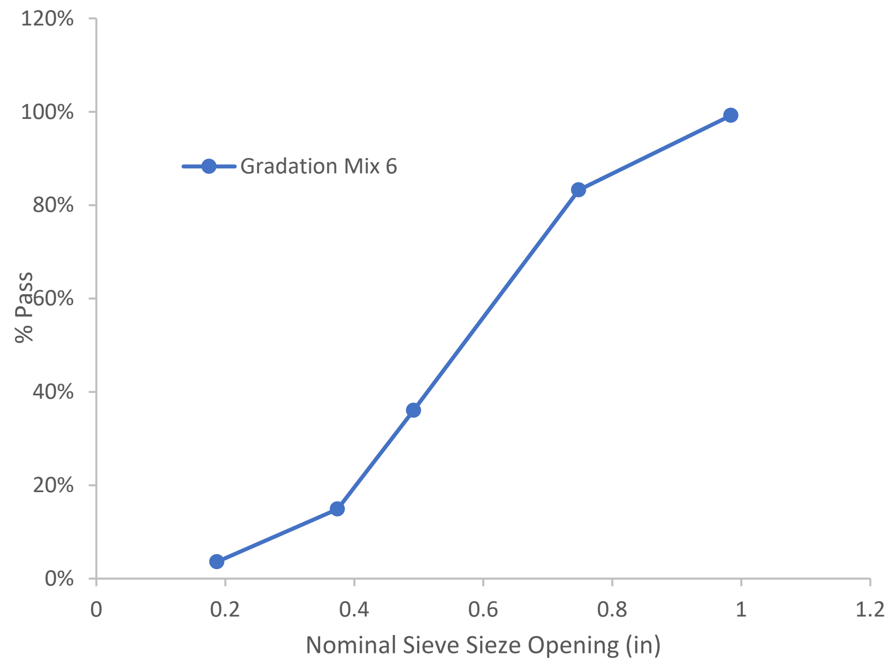

Figure 51. Mix 6 coarse aggregate gradation

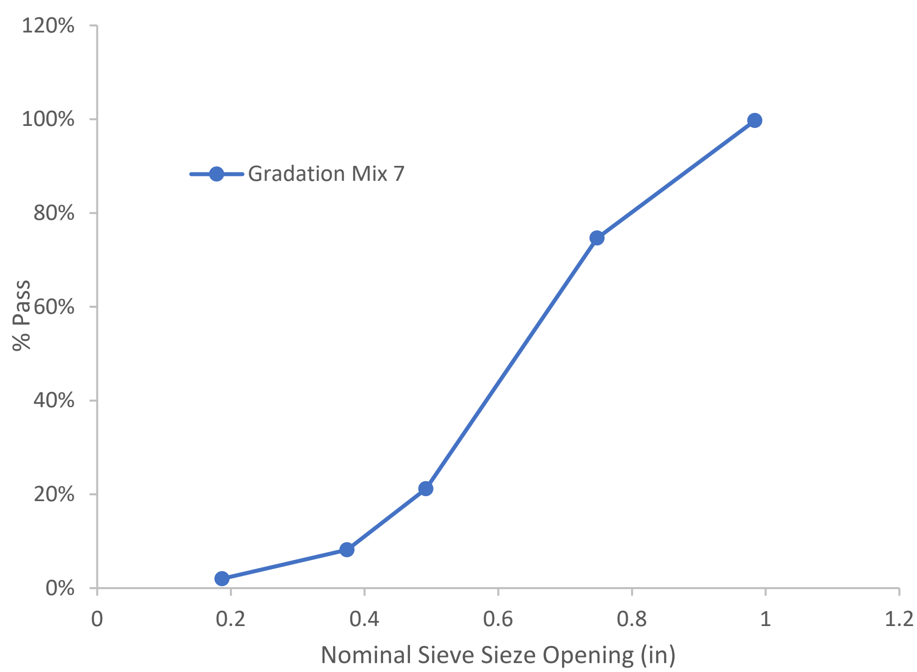

Figure 52. Mix 7 coarse aggregate gradation

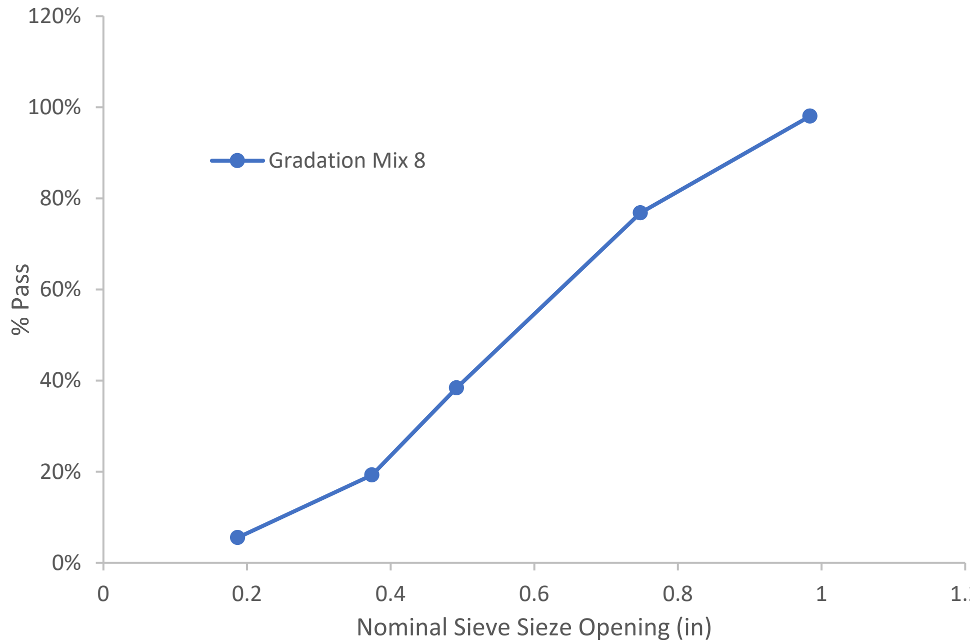

Figure 53. Mix 8 coarse aggregate gradation

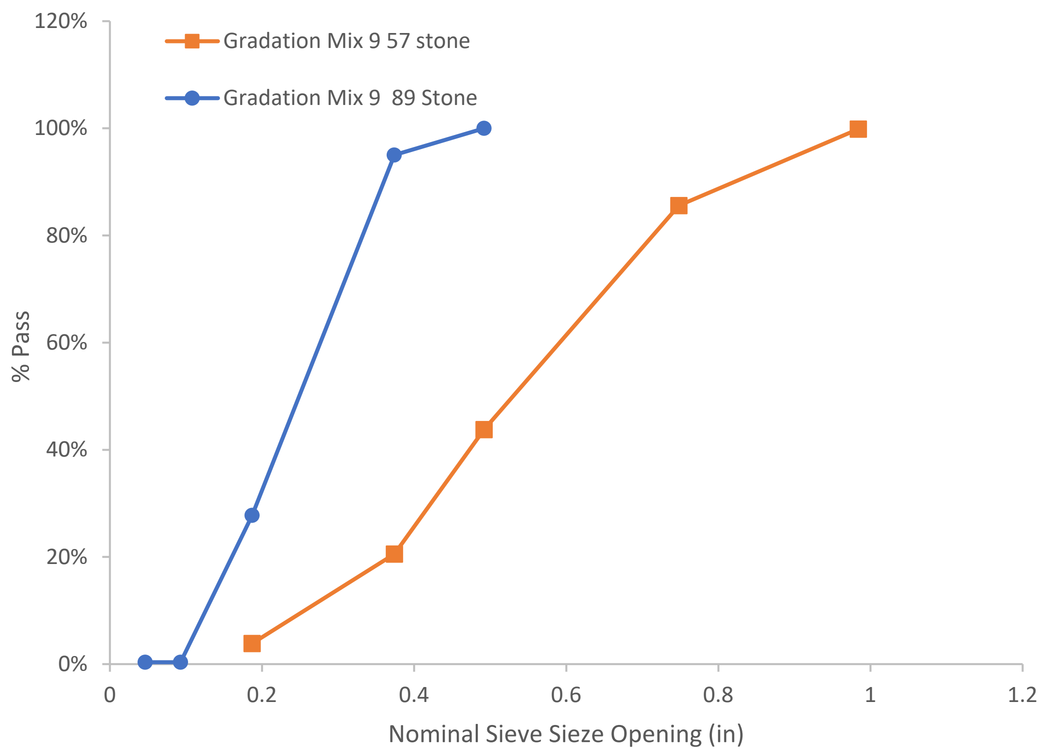

Figure 54. Mix 9 coarse aggregate gradations

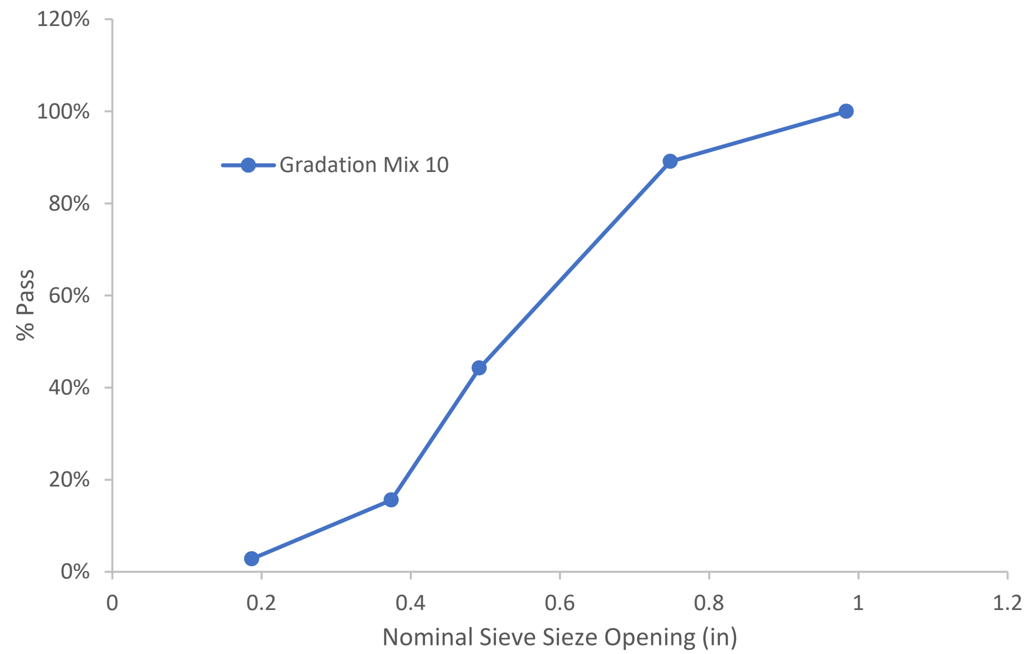

Figure 55. Mix 10 coarse aggregate gradation

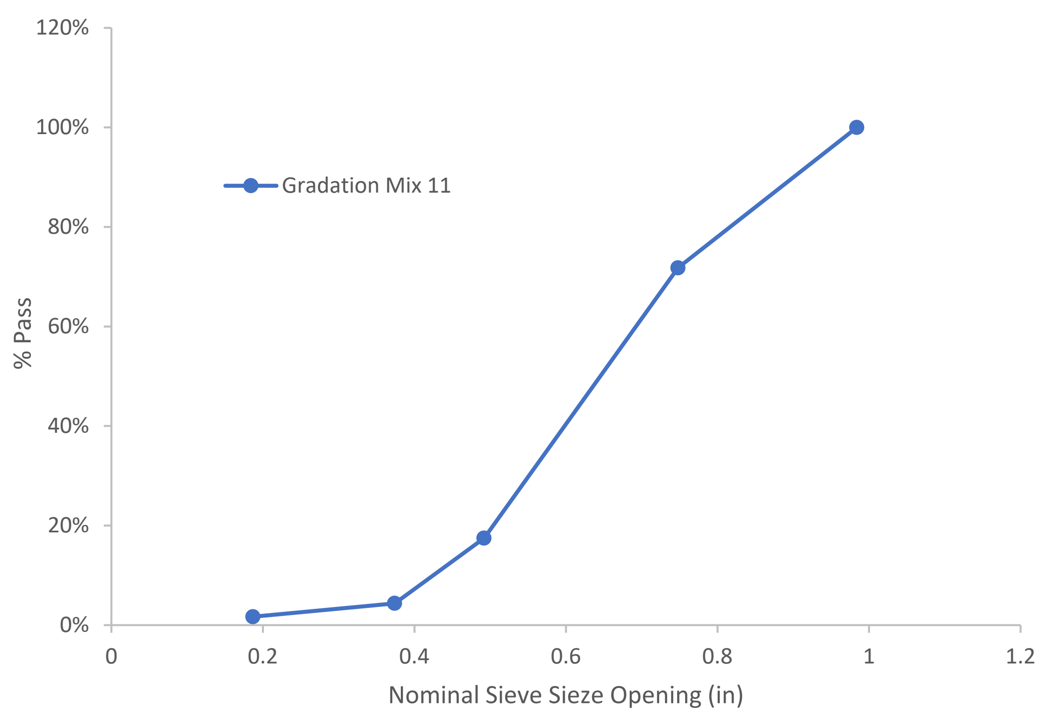

Figure 56. Mix 11 coarse aggregate gradation

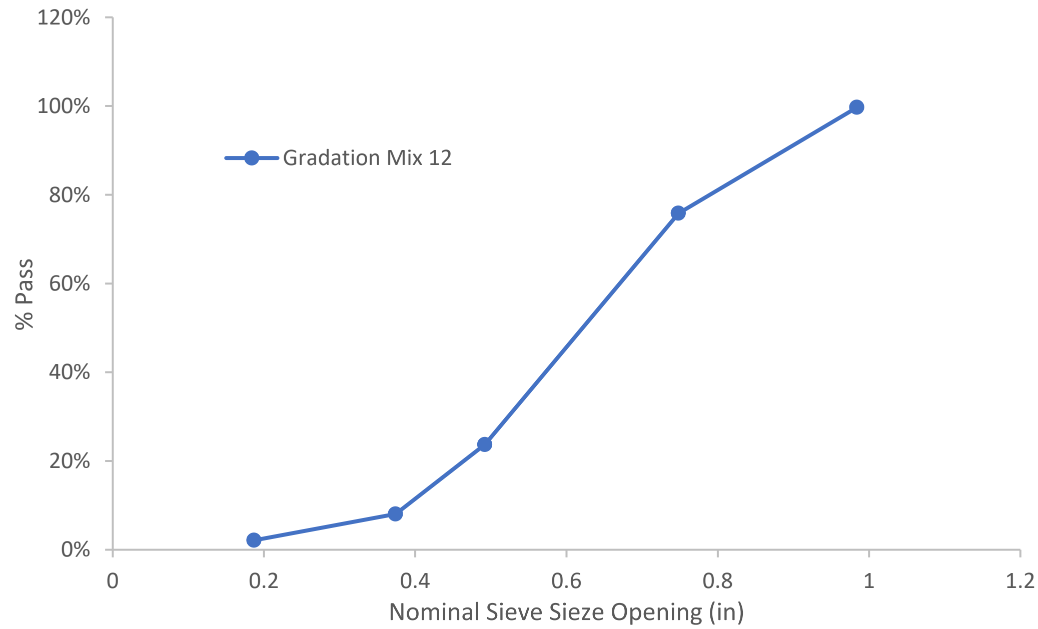

Figure 57. Mix 12 coarse aggregate gradation

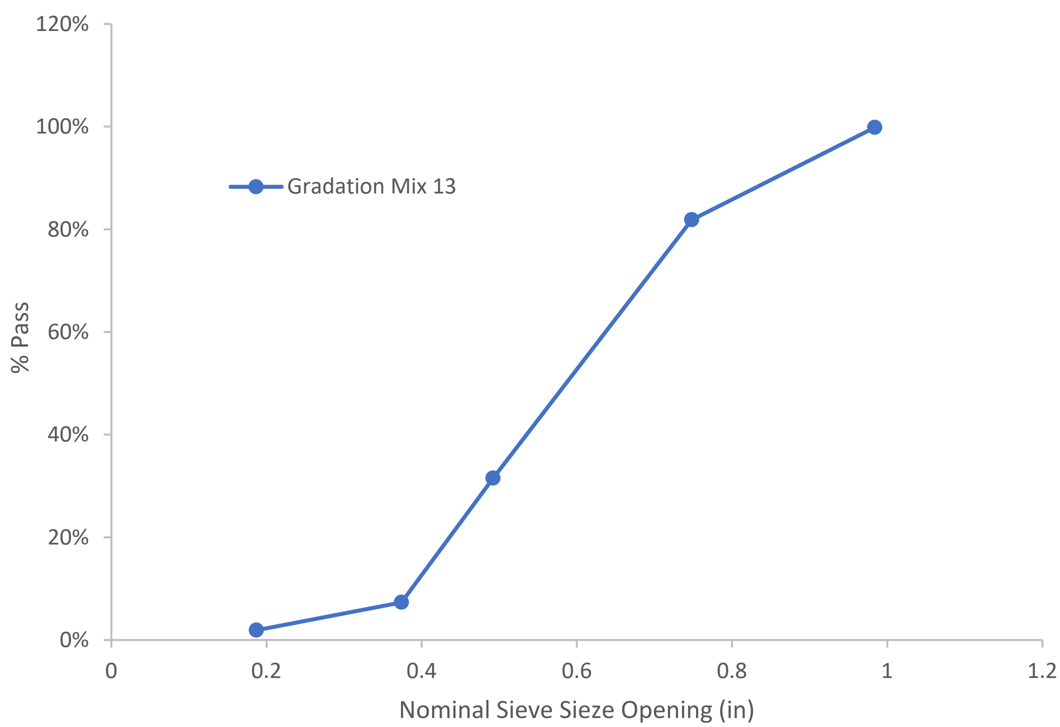

Figure 58. Mix 13 coarse aggregate gradation

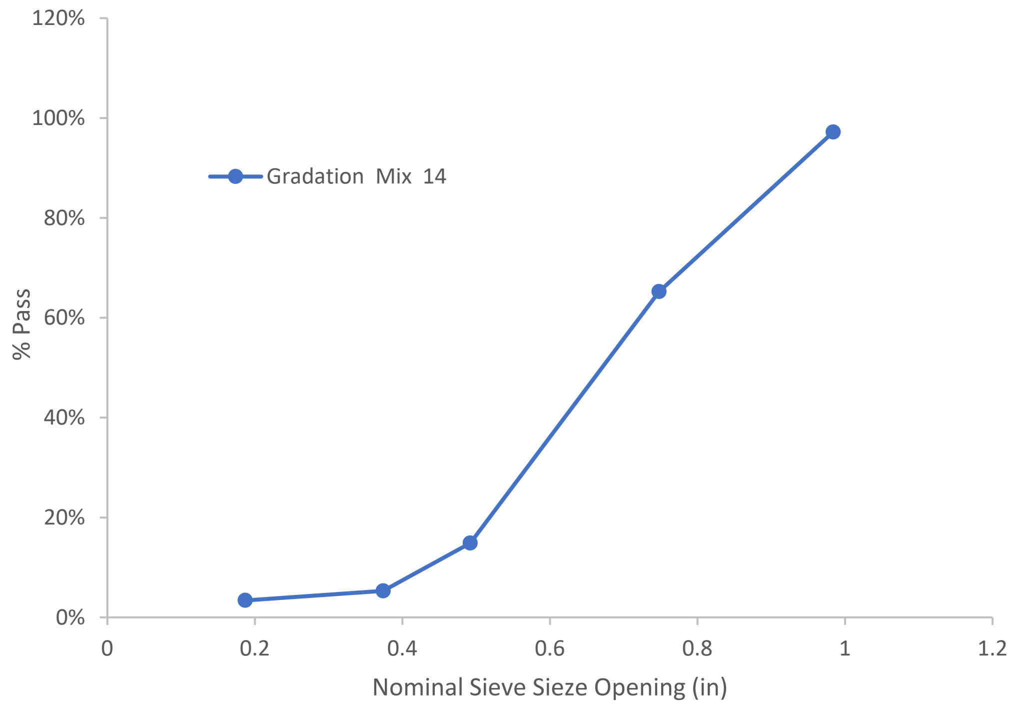

Figure 59. Mix 14 coarse aggregate gradation

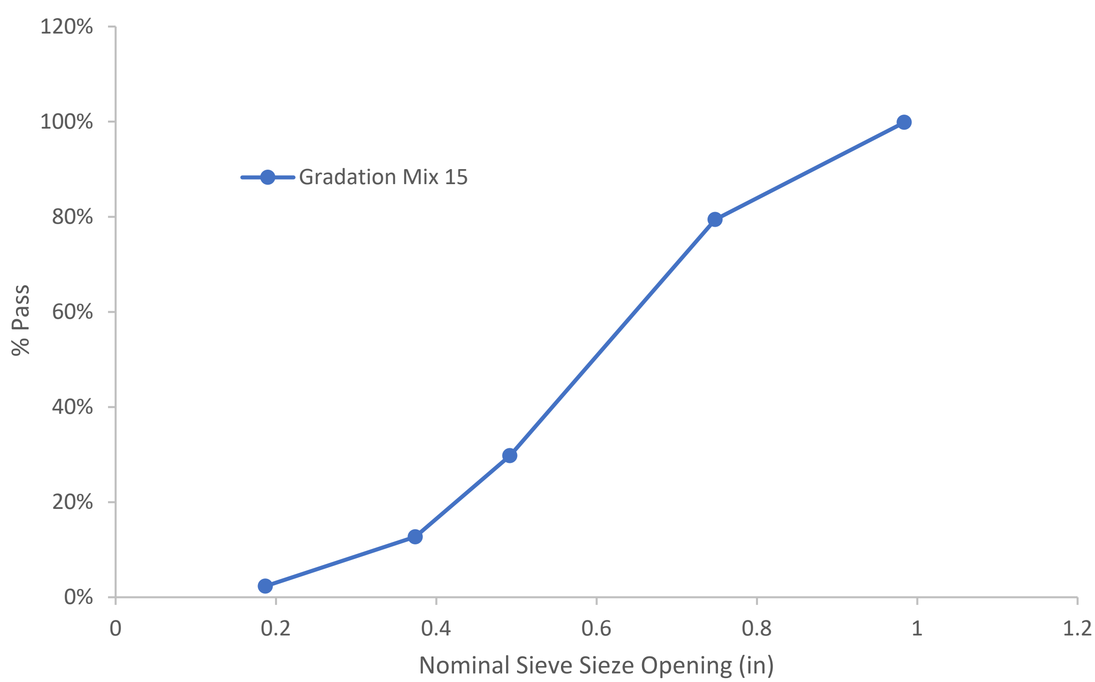

Figure 60. Mix 15 coarse aggregate gradation

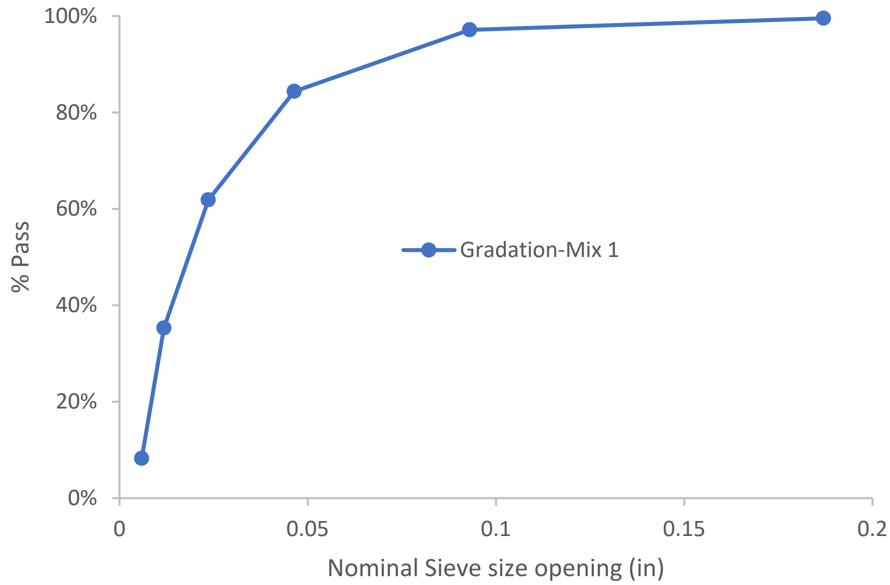

Figure 61. Mix 1 fine aggregate gradation

.

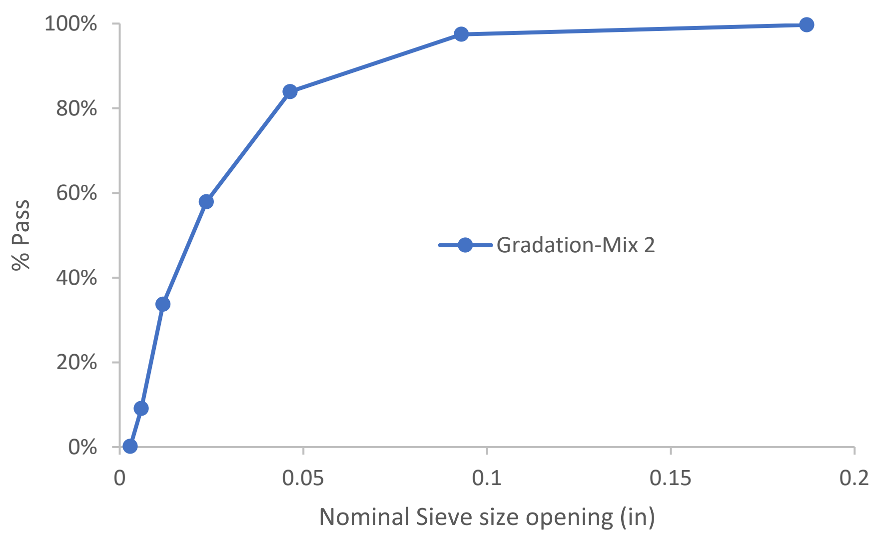

Figure 62. Mix 2 fine aggregate gradation

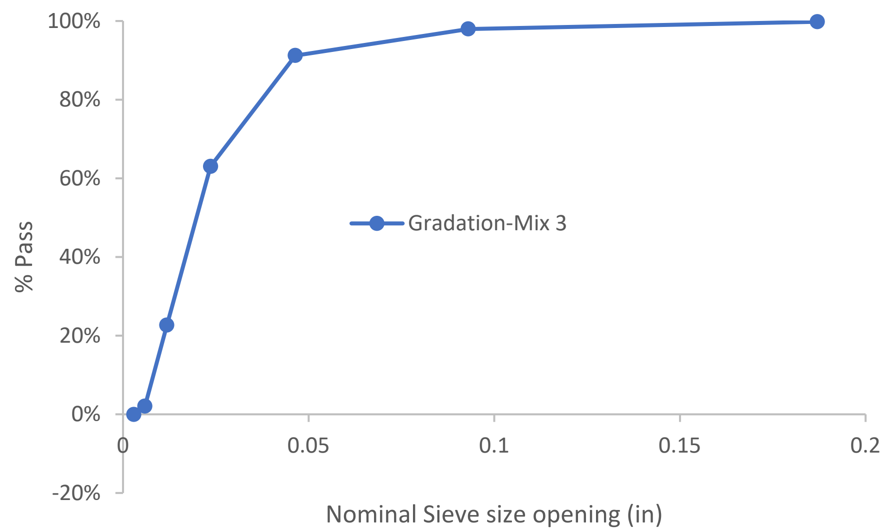

Figure 63. Mix 3 fine aggregate gradation

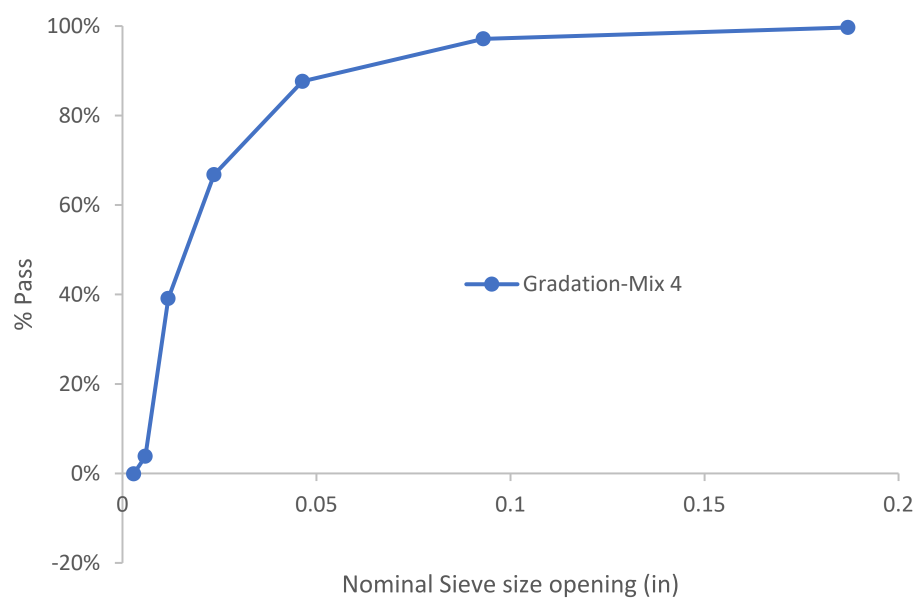

Figure 64. Mix 4 fine aggregate gradation

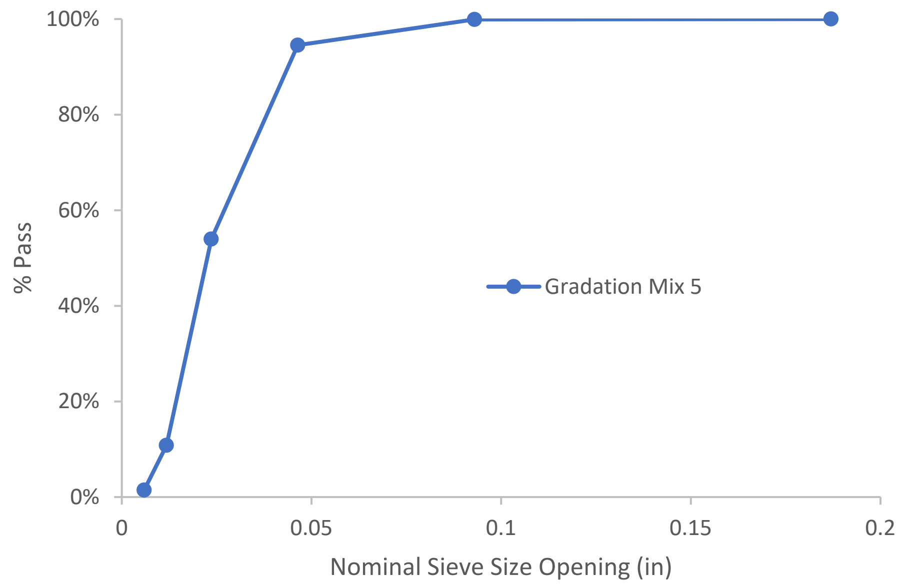

Figure 65. Mix 5 fine aggregate gradation

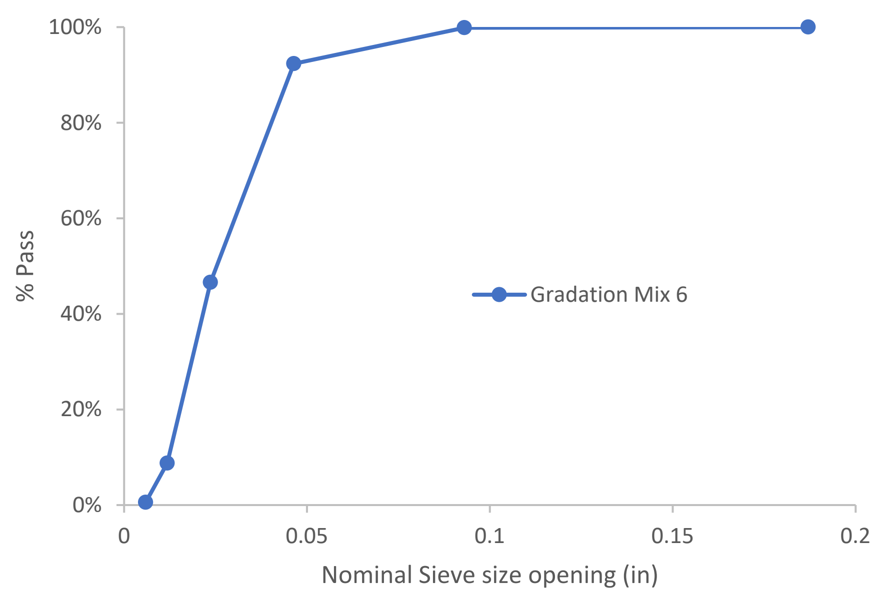

Figure 66. Mix 6 fine aggregate gradation

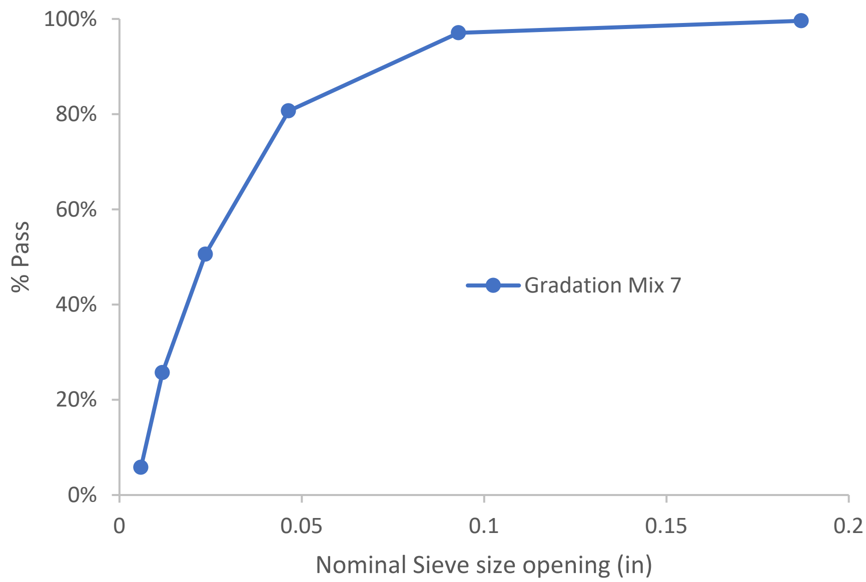

Figure 67. Mix 7 fine aggregate gradation

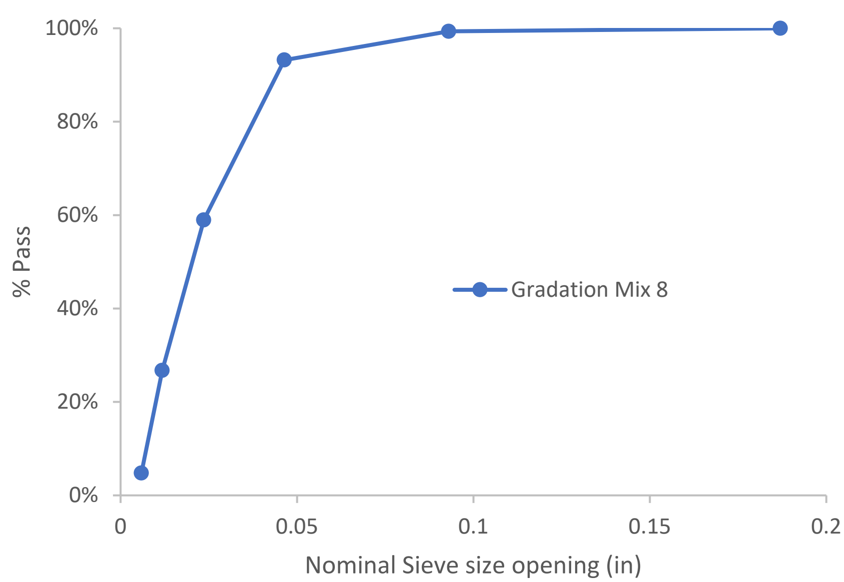

Figure 68. Mix 8 fine aggregate gradation

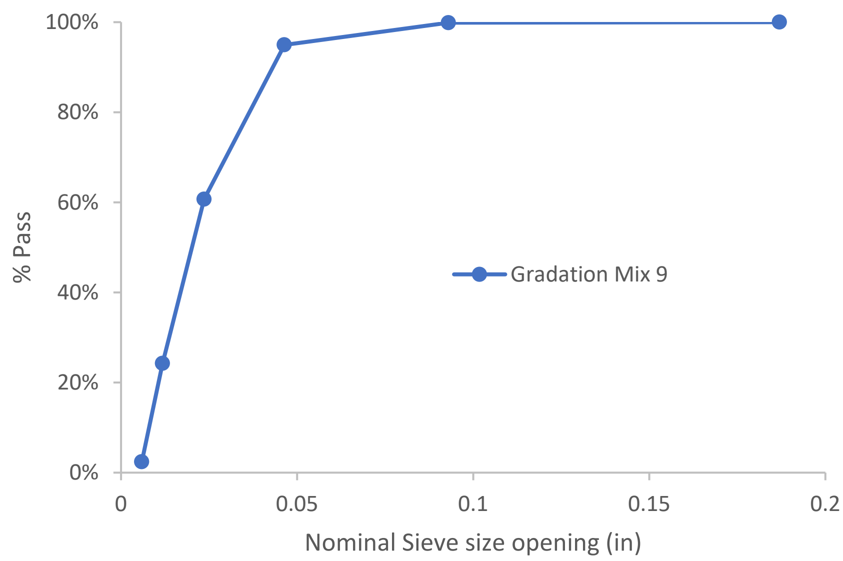

Figure 69. Mix 9 fine aggregate gradation

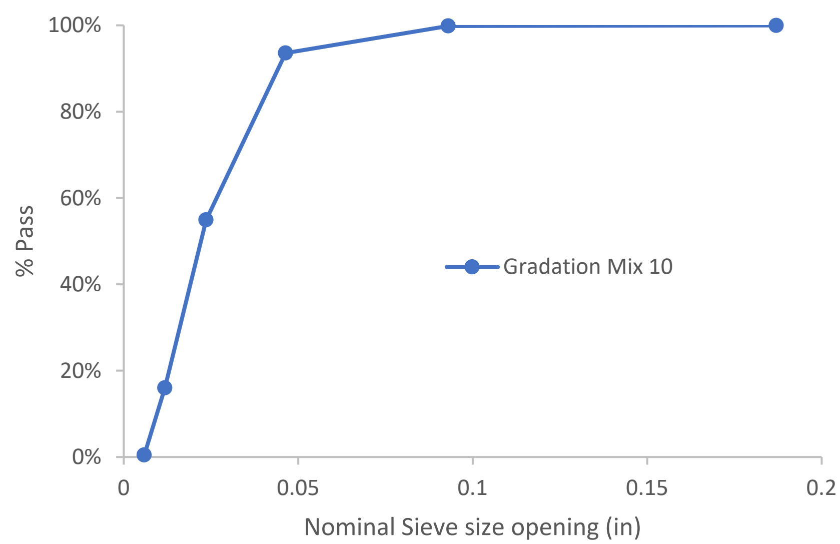

Figure 70. Mix 10 fine aggregate gradation

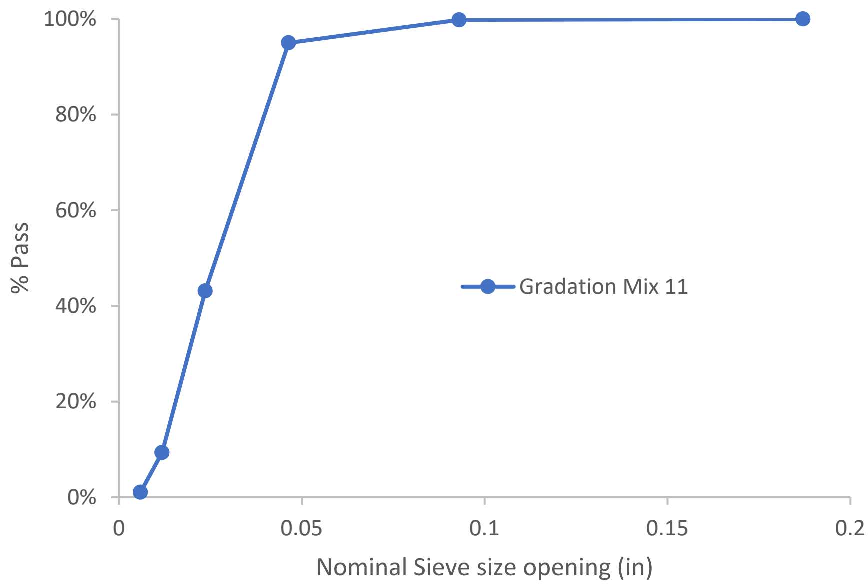

Figure 71. Mix 11 fine aggregate gradation

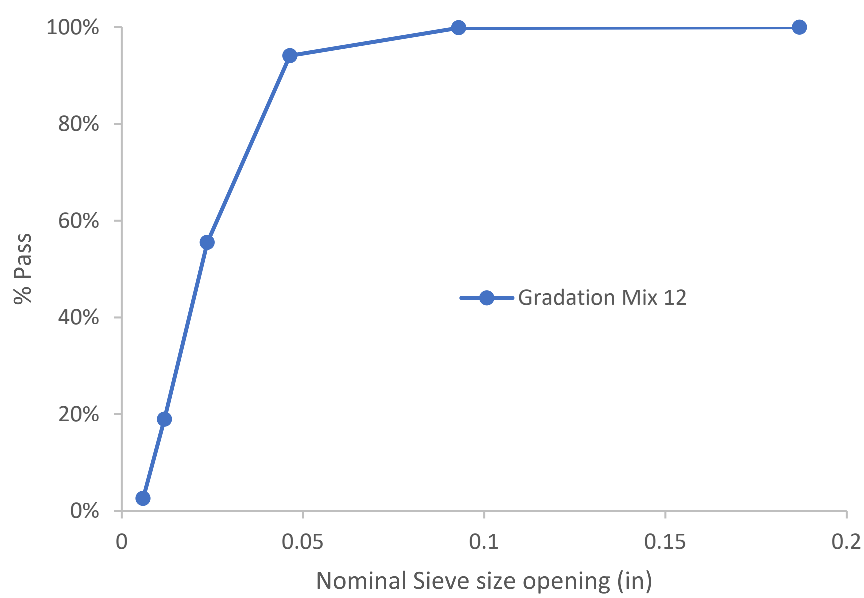

Figure 72. Mix 12 fine aggregate gradation

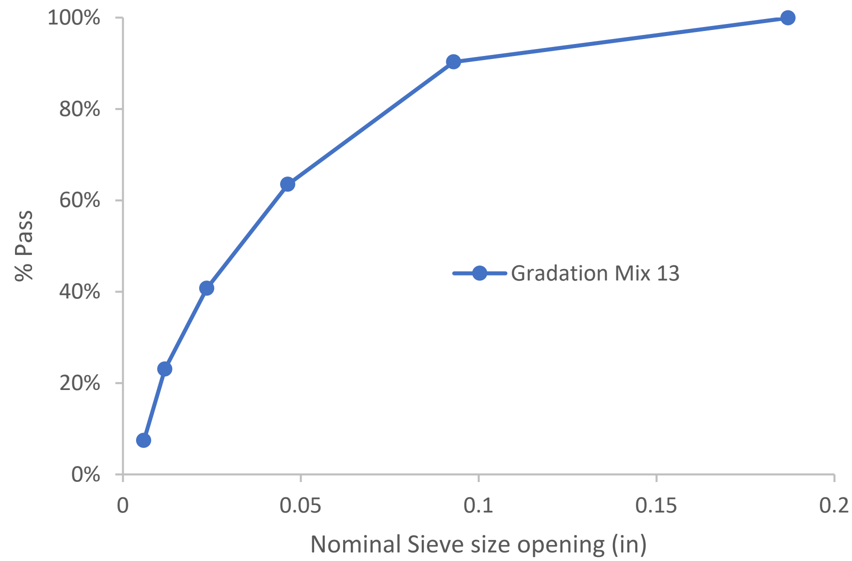

Figure 73. Mix 13 fine aggregate gradation

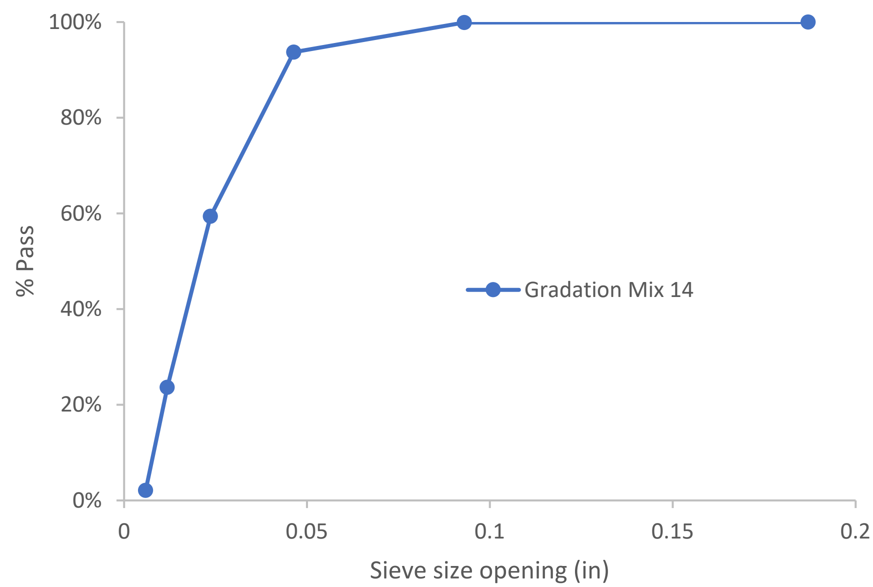

Figure 74. Mix 14 fine aggregate gradation

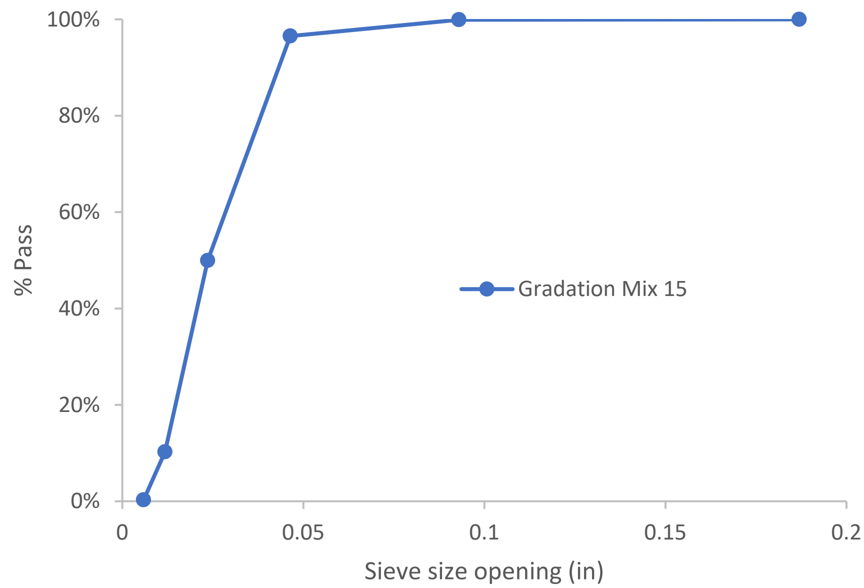

Figure 75. Mix 15 fine aggregate gradation

4.2.2. Cementitious Materials Characterization

Table 68 shows the cementitious material specific gravities measured using gas pycnometry and LOI. Table 69 shows the cementitious material particle size distribution measured using laser particle diffraction.

Table 68. Cementitious material specific gravity and LOI

Mix	Mix	Specific Gravity	% LOI
1	Cement - Type IL	3.12	6.68
	Fly Ash - Class F	2.51	2.4
2	Cement - Type IL	3.14	6.42
	Fly Ash - Class F	2.55	2.55
3	Cement - Type II (MH)	3.18	5.04
	Fly Ash - Class F	2.49	2.51
	Slag	2.96	0.13
4	Cement - Type II (MH)	3.23	5.27
	Slag	3	-0.13
5	Cement - Type IL	3.2	5.33
	Slag	3	0.67

6	Cement - Type IL	3.23	5.3
	Slag	3.03	1.17
7	Cement - Type IL	3.1	5.78
	Fly Ash - Class F	2.52	2.55
8	Cement - Type IL	3.14	6.5
	Slag	2.95	0.14
9	Cement - Type IL	3.17	5.83
	Slag	2.94	-0.06
10	Cement - Type IL	3.15	5.38
	Slag	2.95	0.64
11	Cement - Type IL	3.16	2.23
	Slag	2.97	0.26
12	Cement - Type IL	3.23	5.22
	Slag	2.94	1.16
13	Cement - Type IL	3.21	1.89
	Slag	2.94	0.87
14	Cement - Type IL	3.15	8.54
	Metakaolin	2.83	0.87
	Slag	2.96	-0.33
15	Cement - Type IL	3.13	6.39
	Fly Ash - Class F	2.46	3.07

Table 69. Cementitious material particle size distributions

Mix	Material	dv 10 (um)	dv 50 (um)	dv 90 (um)
1	Cement - Type IL	1.83	10.67	27.61
	Fly Ash - Class F	7.96	17.77	58.10
2	Cement - Type IL	2.22	10.73	27.11
	Fly Ash - Class F	7.72	16.74	58.22
3	Cement - Type II (MH)	3.02	12.32	33.78
	Fly Ash - Class F	5.88	11.03	67.61
	Slag	2.43	11.65	26.19
4	Cement - Type II (MH)	2.38	11.69	33.74
	Slag	2.40	11.60	26.19
5	Cement - Type IL	1.98	9.67	24.21
	Slag	2.25	11.33	25.50
6	Cement - Type IL	1.85	9.40	23.58
	Slag	2.27	11.17	24.75
7	Cement - Type IL	2.10	9.30	21.04
	Fly Ash - Class F	5.37	16.95	75.00

8	Cement - Type IL	2.38	10.14	27.49
	Slag	2.27	12.07	29.91
9	Cement - Type IL	1.81	10.08	28.10
	Slag	2.16	11.58	28.73
10	Cement - Type IL	1.74	9.37	23.84
	Slag	2.01	10.75	21.75
11	Cement - Type IL	2.34	12.53	36.84
	Slag	2.30	12.30	29.27
12	Cement - Type IL	1.62	9.13	24.96
	Slag	1.96	11.14	25.75
13	Cement - Type IL	2.62	12.07	36.58
	Slag	2.21	12.29	29.72
14	Cement - Type IL	2.45	9.71	22.59
	Metakaolin	2.25	12.14	28.44
	Slag	0.32	8.63	35.89
15	Cement - Type IL	2.22	10.49	27.62
	Fly Ash - Class F	3.93	12.06	35.61

4.2.3. Compression Results

The 91-day concrete compressive strengths were measured according to ASTM C39 [86] using the same cylinders used for resistivity tests after the completion of the resistivity measurements. The average 91-day compression strength results are shown in Table 70. The average compression strength for samples fabricated in the laboratory and the field exceeded the design strength in all mixes studied, as shown in Figure 76. The compression strength standard deviation was calculated for the laboratory and field samples per ASTM C670 [6], and is shown as the error bars in Figure 76. All mixtures were significantly above their 28-day design strengths at 91 days.

Table 70. Compression tests results

Det.	Mix 1	Mix 2	Mix 3	Mix 4	Mix 5	Mix 6	Mix 7	Mix 8	Mix 9	Mix 10	Mix 11	Mix 12	Mix 13	Mix 14	Mix 15
28-d Design Strength	5500	5500	5500	5500	5500	5500	4000	5500	3400	5500	5500	3400	5500	5500	4500
1	7340	6300	9480	6790	7180	8070	6850	8100	4700	8700	8630	7470	6970	7610	6580
2	7770	6270	9230	8400	5500	7730	6780	8170	5530	8670	7790	6650	6510	8110	6550
3	n/a	n/a	n/a	8960	7170	8590	6400	7980	5470	8360	7390	5950	8080	8700	7260
4	7780	6300	9120	8460	7170	8020	6150	8120	5580	8340	7310	7080	6200	7770	6950
5	n/a	n/a	n/a	8820	7670	8200	6990	7220	5050	8150	6880	5640	7400	9100	6980
6	n/a	n/a	n/a	8350	7700	8610	6340	7890	4570	8370	7510	5810	8540	9070	6980
7	n/a	n/a	n/a	8400	7430	7890	6900	6980	5260	7770	7650	5890	7740	9110	6980
8	7490	6340	9250	8440	7390	8340	7130	8780	5290	8870	6940	7230	6290	7800	6860
9	7420	6550	9200	8510	7230	8050	6510	8160	4700	8160	7390	6340	6050	8080	6180
10	7570	6440	8920	8880	7020	8200	6310	8090	5340	7810	7640	6090	7020	8370	6710
11	n/a	n/a	n/a	9030	7840	8060	6680	7850	3120	7770	6250	6110	7570	9080	8000
12	7350	6360	9020	8140	7880	8100	6480	8940	5560	7530	7650	7190	6720	8120	6030
13	n/a	n/a	n/a	8400	7810	8640	6560	7070	2220	6760	7880	5780	6730	8950	8190
14	n/a	n/a	n/a	8250	7400	8690	6490	7820	4450	8710	7570	6080	8090	7530	8120
15	n/a	n/a	n/a	8370	7960	6230	7030	6650	3480	7710	7220	5890	6930	8770	8200
16	7610	6570	9440	9500	7340	7950	7020	8060	5810	7990	7760	7470	6050	8050	5960

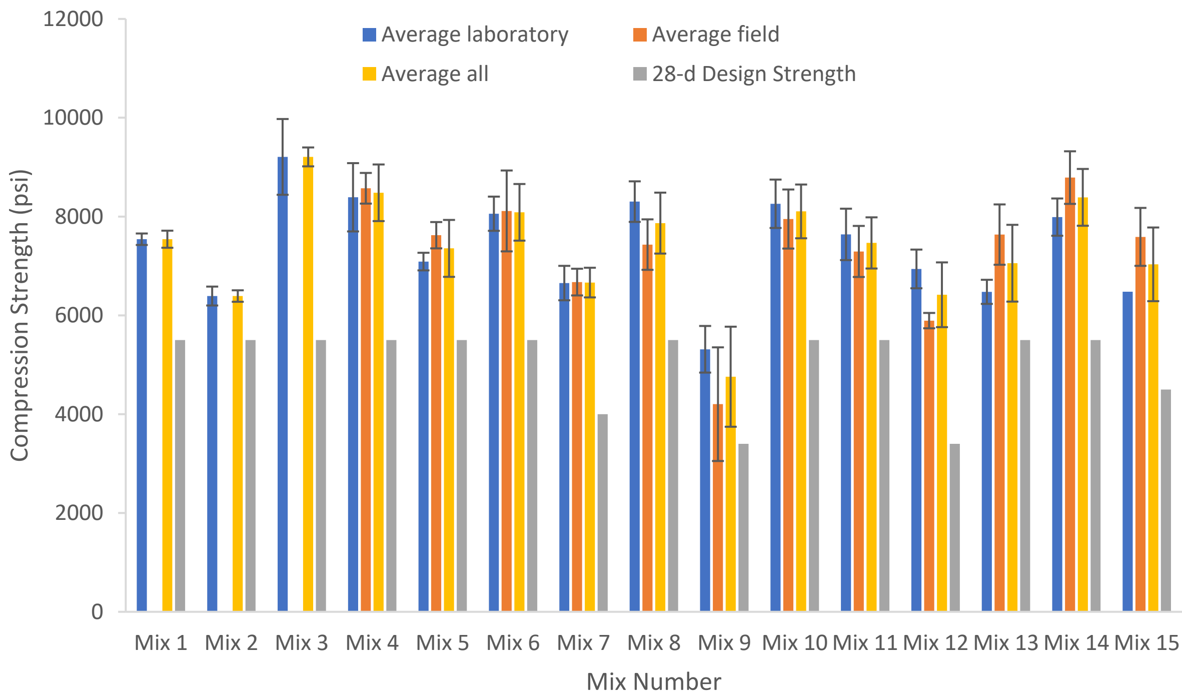

Figure 76. Compression strength results

4.2.4. Resistivity F-statistics

Complete results for resistivity measurements are shown in Appendix A. F-statistics for the concrete resistivity tests performed for each mixture tested were calculated. For a factor to be considered statistically significant for a given mix, the F-statistic computed had to be larger than 5.32. Values above 5.32 are highlighted in green to make it easier to interpret results. Table 71 to Table 82 show the F-statistics calculated following ASTM C1067 [82]. A result higher than 5.32 indicates significance of the factor for the test for the indicated mix at the indicated age. Four tables for each age are presented. The first two tables correspond to the ruggedness analysis for each of the Giatec apparatus for surface and bulk resistivity. The second set of two tables correspond to a comparison between the Giatec and Proceq Resipod equipment. Average percentage difference between field-fabricated specimens and laboratory-fabricated specimens are also shown in the tables. F-statistics for 28 days are presented in Table 71, Table 72, Table 73 and Table 74. The 28-day bulk resistivity was not taken for mixture 1 with the Resipod because of measurement issues. F-statistics for 56 days are presented in Table 75 through Table 78. F-statistics for 91 days are presented in Table 79 through Table 82. Average surface resistivity measurement differences across ages with SURF^{TM} is shown in Figure 77. The same differences are shown in percentages in Figure 78. Average surface resistivity measurement differences across ages for bulk resistivity with RCON^{TM} are shown in Figure 79. The same differences are shown in terms of percentages in Figure 80.

Table 71. F-statistics surface resistivity at 28 days age using SURF^{TM}

Factor	Mix 1	Mix 2	Mix 3	Mix 4	Mix 5	Mix 6	Mix 7	Mix 8	Mix 9	Mix 10	Mix 11	Mix 12	Mix 13	Mix 14	Mix 15	# Significant
Frequency	0.0	0.2	0.3	0.4	0.0	0.4	0.1	10.1	0.2	0.5	0.0	0.0	0.8	0.5	5.7	2
Temperature control	0.2	0.9	1.0	15.8	0.8	1.7	1.2	3.7	0.1	18.5	1.8	0.3	1.7	0.0	4.0	2
Time of demolding	7.6	12.1	1.0	17.3	18.0	22.3	0.1	10.1	0.1	54.9	1.1	6.2	0.3	11.9	11.0	10
Limewater	3.4	0.9	4.5	6.9	0.0	0.8	0.3	30.2	0.1	56.8	0.9	5.7	3.8	6.4	69.9	6
Sample moisture state during testing	9.4	10.9	0.8	0.5	1.2	10.2	1.8	126.5	1.1	14.3	1.5	2.8	0.1	2.3	6.4	6
Sample production	12.9	23.8	32.6	15.7	0.3	71.3	13.8	500.2	8.3	25.8	21.7	11.7	364.6	40.6	538.4	14

Table 72. F-statistics bulk resistivity 28 days age using RCON^{TM}

Factor	Mix 1	Mix 2	Mix 3	Mix 4	Mix 5	Mix 6	Mix 7	Mix 8	Mix 9	Mix 10	Mix 11	Mix 12	Mix 13	Mix 14	Mix 15	# Significant
Frequency	10.2	81.4	1.0	0.3	2.5	1.9	3.2	66.2	1.3	6.0	1.4	1.0	24.0	22.2	73.4	7
Temperature control	0.0	3.1	0.0	13.3	0.0	1.9	3.9	34.0	0.1	3.6	0.8	0.6	3.5	1.1	0.6	2
Time of demolding	7.6	18.8	1.1	13.6	28.7	1.7	0.0	6.7	0.1	31.6	3.2	3.8	0.1	28.3	0.2	7
Limewater	23.9	0.0	3.5	0.3	0.0	2.0	0.9	23.5	0.6	17.1	2.3	5.9	2.5	27.4	25.3	6
Sample moisture state during testing	2.1	8.6	1.4	0.9	1.6	5.9	2.8	113.5	0.7	2.7	0.4	0.6	0.0	18.8	8.7	5
Sample production	124.3	2549.0	112.4	105.0	71.6	42.9	0.2	583.8	15.4	90.2	6.8	3.1	106.3	19.5	6.4	13

Table 73. F-statistics surface resistivity at 28 days age comparing resistivity equipment manufacturer

Factor	Mix 1	Mix 2	Mix 3	Mix 4	Mix 5	Mix 6	Mix 7	Mix 8	Mix 9	Mix 10	Mix 11	Mix 12	Mix 13	Mix 14	Mix 15	# Significant
Manufacturer	65.3	221.3	318.7	94.5	97.7	313.7	135.2	475.1	1.8	428.0	19.0	32.4	32.2	135.0	50.2	14
Temperature control	0.1	0.0	0.2	13.2	0.4	1.2	2.4	15.7	0.0	13.7	2.6	0.5	2.3	0.1	1.0	3
Time of demolding	5.7	11.1	0.0	11.2	60.6	27.1	0.2	11.3	0.1	80.4	1.9	5.4	0.0	19.7	11.0	10
Limewater	7.1	0.4	8.0	4.5	5.2	0.7	0.0	36.5	0.1	107.8	0.9	6.4	3.0	4.4	26.9	6
Sample moisture state during testing	6.7	28.0	0.1	0.9	5.0	6.3	9.2	113.8	0.8	16.5	1.0	3.1	0.2	2.3	3.1	6
Sample production	30.7	116.2	426.9	0.0	0.0	55.0	55.2	531.8	6.4	26.6	16.9	9.0	450.1	37.2	181.7	13

Table 74. F-statistics bulk resistivity at 28 days age comparing resistivity equipment manufacturer

Factor	Mix 1	Mix 2	Mix 3	Mix 4	Mix 5	Mix 6	Mix 7	Mix 8	Mix 9	Mix 10	Mix 11	Mix 12	Mix 13	Mix 14	Mix 15	# Significant
Manufacturer	-	1677.6	0.3	45.4	11.2	40.3	5.8	1.2	5.3	245.0	36.0	24.2	243.1	7.3	2.0	10
Temperature control	-	3.0	1.1	11.6	0.1	0.1	0.0	15.2	0.1	6.8	0.5	0.3	2.9	0.7	0.7	3
Time of demolding	-	6.5	0.8	13.7	19.1	39.2	3.5	0.8	0.1	32.1	2.6	3.9	0.7	27.9	4.4	6
Limewater	-	3.1	0.0	0.6	0.1	1.2	1.4	30.5	0.7	21.7	2.9	6.8	5.2	38.2	7.3	5
Sample moisture state during testing	-	8.1	0.6	0.7	1.9	6.4	0.0	105.1	0.6	5.4	0.7	1.3	0.1	25.1	1.2	5
Sample production	-	532.8	13.9	57.7	22.0	89.8	2.6	500.5	11.6	31.5	16.4	7.8	283.9	95.5	4.3	12

Table 75. F-statistics surface resistivity at 56 days age using SURF™

Factor	Mix 1	Mix 2	Mix 3	Mix 4	Mix 5	Mix 6	Mix 7	Mix 8	Mix 9	Mix 10	Mix 11	Mix 12	Mix 13	Mix 14	Mix 15	# Significant
Frequency	0.4	0.9	1.0	0.2	0.0	0.0	5.8	1.1	0.1	0.2	0.0	0.0	0.2	1.4	1.8	1
Temperature control	0.3	0.8	9.6	16.2	0.8	1.4	3.0	5.2	0.0	1.4	1.2	1.1	2.9	4.6	8.4	3
Time of demolding	4.5	0.2	15.7	25.9	38.7	14.6	9.7	0.0	0.0	8.5	1.3	2.5	0.2	8.7	18.5	8
Limewater	0.3	4.2	1.6	3.5	2.1	6.1	0.1	1.0	0.3	13.1	0.5	1.1	0.6	1.4	69.5	3
Sample moisture state during testing	5.4	1.2	9.4	0.0	2.3	12.8	4.8	41.9	1.3	10.2	1.0	0.8	2.0	20.1	0.5	6
Sample production	2.6	7.6	605.9	129.4	3.6	18.0	16.7	349.8	7.3	18.2	9.9	1.8	364.7	35.8	464.0	12

Table 76. F-statistics bulk resistivity 56 days age using RCON™

Factor	Mix 1	Mix 2	Mix 3	Mix 4	Mix 5	Mix 6	Mix 7	Mix 8	Mix 9	Mix 10	Mix 11	Mix 12	Mix 13	Mix 14	Mix 15	# Significant
Frequency	7.1	0.2	1.3	0.4	4.2	14.2	1.5	9.8	2.1	8.3	2.9	4.4	2.9	10.9	81.3	6
Temperature control	0.3	0.0	0.1	0.3	0.0	0.7	0.0	0.2	0.2	0.5	0.2	0.5	2.7	8.4	0.0	1
Time of demolding	1.0	0.1	3.2	7.7	48.7	16.0	0.5	0.2	0.2	0.8	0.8	2.3	0.6	3.7	0.0	3
Limewater	0.1	7.4	0.1	0.4	0.5	3.7	0.5	0.0	0.1	0.2	0.9	2.9	1.8	19.6	59.6	3
Sample moisture state during testing	2.7	0.0	5.9	1.5	16.1	43.9	0.1	3.0	0.2	0.0	0.0	0.9	0.2	11.0	1.8	4
Sample production	51.3	9.6	78.2	60.6	152.7	14.2	4.1	36.1	13.8	28.0	0.0	3.2	8.5	24.6	134.8	12

Table 77. F-statistics surface resistivity at 56 days age comparing resistivity equipment manufacturer

Factor	Mix 1	Mix 2	Mix 3	Mix 4	Mix 5	Mix 6	Mix 7	Mix 8	Mix 9	Mix 10	Mix 11	Mix 12	Mix 13	Mix 14	Mix 15	# Significant
Manufacturer	54.5	12.9	1116.9	175.2	211.6	1525.0	255.4	374.8	2.3	260.1	17.9	33.9	34.3	167.2	97.4	14
Temperature control	1.7	0.6	5.7	19.6	1.1	13.2	10.1	23.6	0.2	0.2	2.1	1.0	6.1	9.1	3.3	7
Time of demolding	8.7	0.1	16.7	28.3	111.2	118.4	8.3	3.6	0.0	22.2	1.7	4.0	0.4	8.4	14.1	9
Limewater	6.1	5.5	0.1	1.8	11.0	12.4	0.5	10.7	0.3	13.9	0.5	1.3	1.0	2.9	62.0	7
Sample moisture state during testing	11.0	1.5	4.3	1.0	15.3	72.6	1.2	79.4	1.1	13.2	0.5	1.5	2.1	13.5	2.8	6
Sample production	4.7	8.5	807.5	140.4	0.2	57.6	25.2	692.6	5.8	11.6	10.3	0.6	471.7	34.0	408.2	12

Table 78. F-statistics bulk resistivity at 56 days age comparing resistivity equipment manufacturer

Factor	Mix 1	Mix 2	Mix 3	Mix 4	Mix 5	Mix 6	Mix 7	Mix 8	Mix 9	Mix 10	Mix 11	Mix 12	Mix 13	Mix 14	Mix 15	# Significant
Manufacturer	19.8	0.5	16.5	17.3	11.5	1.0	0.3	5.9	1.2	89.9	3.6	2.9	14.5	7.9	16.5	9
Temperature control	0.2	0.3	0.8	21.1	0.0	0.1	1.0	33.7	0.0	0.2	0.9	1.5	0.3	5.2	0.0	2
Time of demolding	7.0	2.1	1.5	23.6	30.1	6.3	2.0	3.5	0.0	22.0	1.7	3.7	1.6	10.9	5.9	7
Limewater	2.4	4.8	0.6	1.7	0.4	0.2	0.0	12.6	0.9	13.2	1.0	4.0	3.1	28.4	1206.6	4
Sample moisture state during testing	1.3	0.3	8.4	0.1	8.3	5.7	0.5	60.9	1.2	25.3	0.1	1.0	0.1	37.4	170.7	7
Sample production	47.3	10.2	401.7	368.8	30.1	4.6	18.9	642.3	14.6	132.2	0.7	0.1	211.0	99.3	2521.0	12

Table 79. F-statistics surface resistivity at 91 days age using SURF^{TM}

Factor	Mix 1	Mix 2	Mix 3	Mix 4	Mix 5	Mix 6	Mix 7	Mix 8	Mix 9	Mix 10	Mix 11	Mix 12	Mix 13	Mix 14	Mix 15	# Significant
Frequency	0.03	0.30	0.03	0.38	1.55	0.02	0.09	0.29	0.10	0.01	0.41	0.04	0.13	1.71	1.28	0
Temperature control	0.22	1.18	8.66	47.32	0.04	1.31	0.03	16.38	0.06	0.01	1.36	0.99	4.74	1.99	3.29	3
Time of demolding	0.17	5.40	5.64	43.97	25.59	10.34	2.33	4.59	0.00	5.93	0.36	4.38	0.59	3.20	7.97	7
Limewater	0.00	2.39	0.00	3.01	0.37	0.02	1.63	43.15	0.25	3.97	0.08	2.15	0.98	4.07	24.79	2
Sample moisture state during testing	1.45	4.43	16.07	6.14	12.27	7.70	6.73	130.55	0.65	0.20	0.40	3.36	2.44	8.16	3.99	7
Sample production	1.00	1.96	211.54	152.09	3.17	5.55	0.41	569.60	3.93	14.69	13.62	1.01	424.24	6.51	83.84	9

Table 80. F-statistics bulk resistivity 91 days age using RCON™

Factor	Mix 1	Mix 2	Mix 3	Mix 4	Mix 5	Mix 6	Mix 7	Mix 8	Mix 9	Mix 10	Mix 11	Mix 12	Mix 13	Mix 14	Mix 15	# Significant
Frequency	36.68	0.61	2.17	4.69	10.56	3.02	3.53	31.21	1.92	117.50	6.34	5.77	19.98	33.85	129.27	9
Temperature control	0.62	0.33	39.31	17.47	1.49	1.39	2.52	37.26	0.00	12.89	0.01	0.84	0.34	15.05	0.00	5
Time of demolding	2.93	0.05	37.20	23.97	19.54	2.16	0.88	7.88	0.01	57.57	0.03	2.50	1.74	3.48	0.06	5
Limewater	35.57	0.57	0.28	4.69	1.56	0.00	5.28	46.42	1.05	0.04	1.60	10.07	20.31	63.71	138.07	6
Sample moisture state during testing	10.77	0.19	51.03	8.71	7.74	4.26	6.80	95.72	0.32	1.17	0.07	5.54	12.12	39.26	50.24	10
Sample production	1142.10	19.34	1320.43	327.64	19.08	7.16	35.82	823.47	3.86	315.06	4.42	0.25	34.80	50.22	82.56	12

Table 81. F-statistics surface resistivity at 91 days age comparing resistivity equipment manufacturer

Factor	Mix 1	Mix 2	Mix 3	Mix 4	Mix 5	Mix 6	Mix 7	Mix 8	Mix 9	Mix 10	Mix 11	Mix 12	Mix 13	Mix 14	Mix 15	# Significant
Manufacturer	4.69	82.32	276.99	423.15	266.77	447.16	69.62	285.14	1.50	137.76	26.98	41.30	32.33	103.80	55.50	13
Temperature control	0.27	0.04	3.25	46.41	4.04	0.00	1.05	47.73	0.29	0.47	1.80	0.86	3.72	7.82	1.02	3
Time of demolding	0.02	8.01	12.63	48.69	51.13	16.72	0.55	17.30	0.11	7.15	0.52	4.46	1.74	3.84	8.36	8
Limewater	0.07	2.16	0.14	3.88	13.07	0.75	0.05	32.96	0.37	7.66	0.26	3.68	2.01	7.53	32.11	5
Sample moisture state during testing	2.13	3.77	8.78	1.22	12.99	9.20	4.17	118.55	0.63	1.84	0.10	5.53	3.23	3.15	10.54	6
Sample production	1.02	6.22	297.71	89.36	28.23	9.45	0.00	542.30	3.22	30.50	8.63	0.67	356.86	1.84	86.81	10

Table 82. F-statistics bulk resistivity at 91 days age comparing resistivity equipment manufacturer

Factor	Mix 1	Mix 2	Mix 3	Mix 4	Mix 5	Mix 6	Mix 7	Mix 8	Mix 9	Mix 10	Mix 11	Mix 12	Mix 13	Mix 14	Mix 15	# Significant
Manufacturer	18.52	0.19	9.14	0.37	1.70	15.04	52.69	22.25	0.28	55.65	3.60	0.29	0.01	12.14	3.02	7
Temperature control	2.77	3.73	24.06	12.13	0.06	0.19	0.63	86.21	0.04	0.00	0.03	1.31	3.41	20.23	0.56	4
Time of demolding	26.32	0.17	30.56	18.79	25.68	8.57	0.01	28.88	0.01	23.35	0.06	3.86	0.56	7.56	0.16	8
Limewater	8.01	2.29	0.64	2.30	0.01	0.41	2.56	80.85	0.74	18.40	1.86	7.26	15.90	39.02	41.56	7
Sample moisture state during testing	6.53	2.06	32.94	4.91	11.42	0.96	14.67	208.50	0.19	8.44	0.13	4.25	5.23	22.76	11.85	8
Sample production	509.49	75.27	827.85	169.32	3.07	8.54	21.57	1330.98	4.81	129.25	2.02	0.19	75.15	56.51	39.42	11

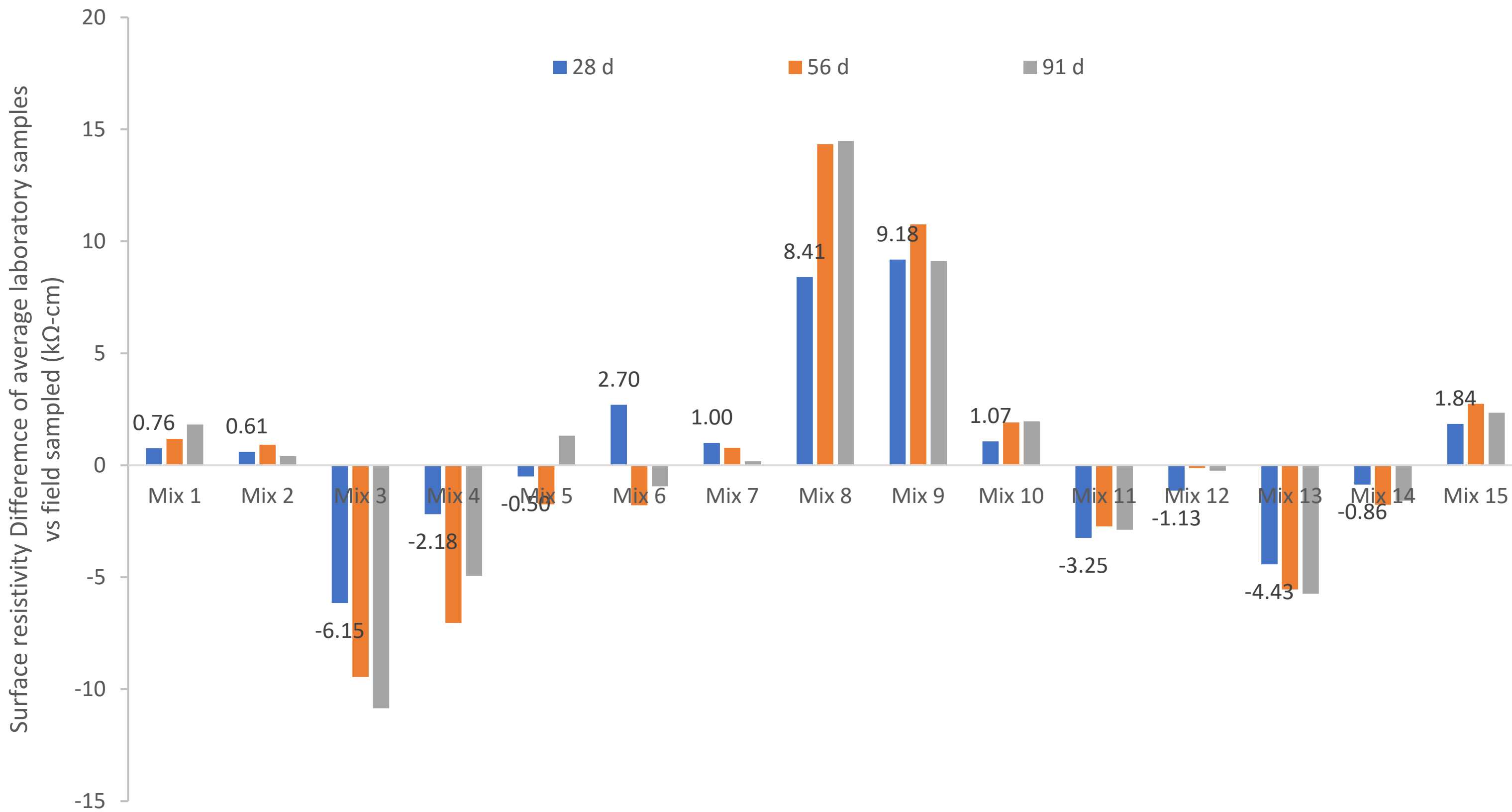

Figure 77. Difference of averages of surface resistivity between laboratory samples vs. field samples with SURF^{TM} (kΩ-cm)

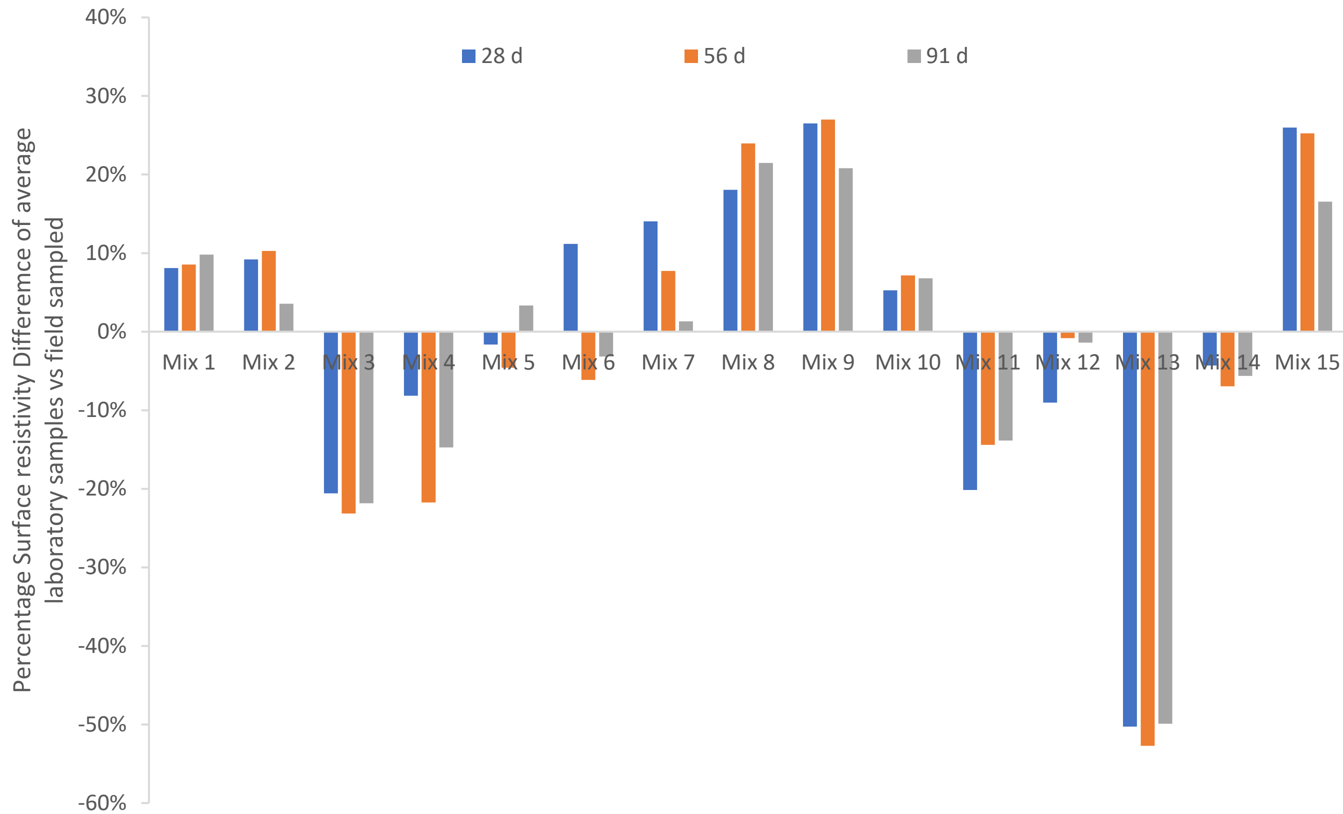

Figure 78. Percentage surface resistivity difference of average laboratory samples vs. field sampled using SURF™

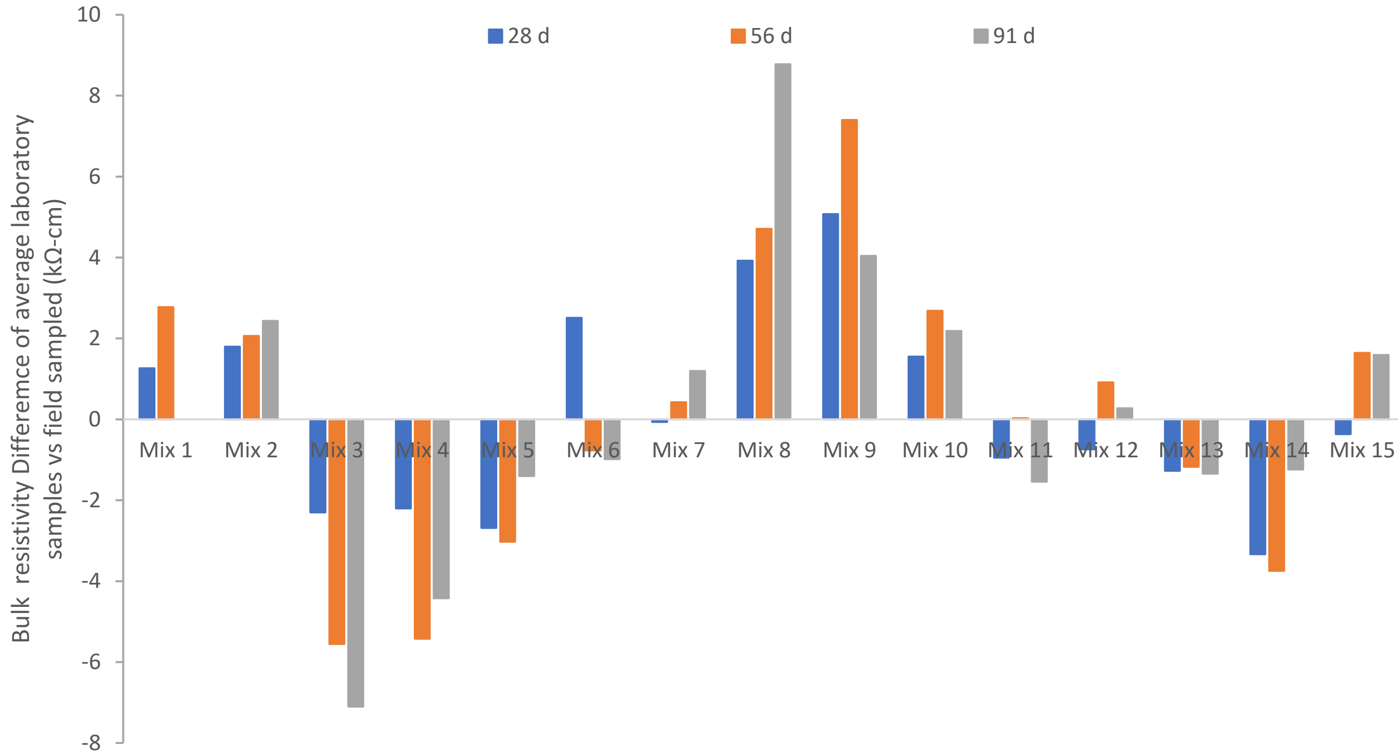

Figure 79. Difference of average laboratory samples vs. field sampled (kΩ-cm) for RCON[TM]

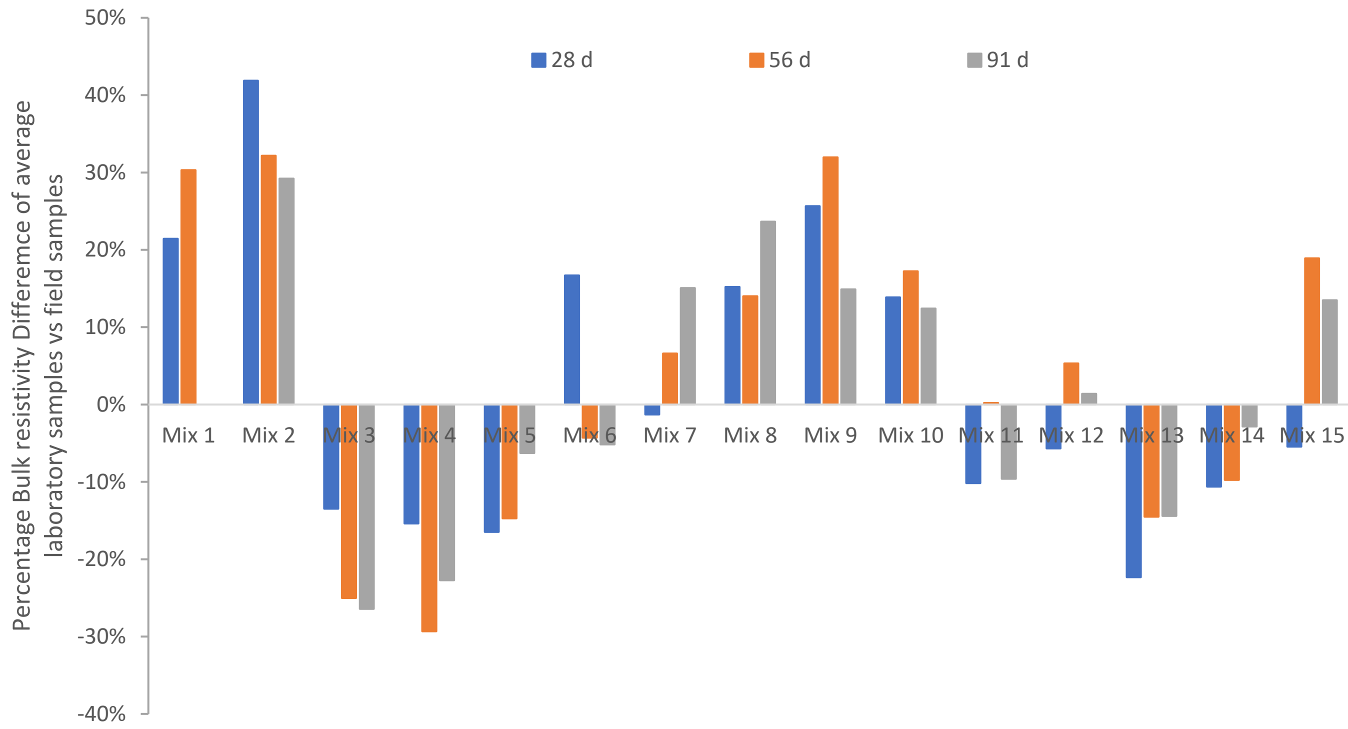

Figure 80. Percentage bulk resistivity difference of average laboratory samples vs. field samples for RCON^{TM}

4.3. Analysis of Results

The number of mixtures where a factor was found to be significant was examined to determine the relative significance of the factor in providing reliable resistivity measurements. The surface resistivity results measured using the SURF™ showed that frequency was only significant for two of the 15 mixtures. Overall, this can be interpreted as the frequency has only a minor effect on the surface resistivity measurements. Measurements with the RCON™ showed moderate sensitivity to frequency, where between 27% and 47% of the mixtures were significant. Temperature control was found to be significant for only a few mixtures with the SURF™ (7% to 20%) and RCON™ (13% to 27%). Time of demolding was found to be significant 40% to 67% of the time when using the SURF™ and only moderately significant with the RCON™ (20 to 47% of the time). This may be because providing access to moisture during wet curing impacts the surface more than the interior of the sample, especially for 28-day measurements. Limewater curing in a communal tank vs. in individual buckets was found significant in 40% of the mixtures in both surface and bulk resistivity at 28 days. Moisture state during testing was found to be statistically significant for 40% of the mixtures at all ages with the SURF™. Moisture state was found to be moderately significant for the RCON™, with 20% to 53% of the mixtures showing significance. The equipment used was found to be highly significant, with 67% to 93% of the mixtures showing significance for surface resistivity, and 47% to 67% of the time for bulk resistivity. Surface resistivity results were on average 17.6% higher at 28 days with the SURF™ than the Resipod. Bulk resistivity results were 3.2% higher at 28 days with the Resipod than RCON™.

The significance of a factor studied is dependent on the variability of the set tested and could indicate different absolute resistivity values for differences of averages between levels in each factor. For instance, for the surface Giatec equipment at 28 days age testing, the highest F-statistic value for sample production registered was 538.4 for mix 15, which corresponds to a difference between levels (offset between lab and field) of 1.84 kΩ-cm, with the laboratory-fabricated samples higher.

Average offsets for surface and bulk resistivity were calculated. There were no trends that held for all ages and mixtures tested, as the resistivity values measured were higher in the field for some mixtures, and higher in the laboratory for other mixtures. For surface resistivity with the SURF™ at 28-day age testing, the average offset of the mixes where the laboratory-fabricated samples resulted in higher resistivity was 4.29 kΩ-cm (15% of the FDOT resistivity uncorrected for geometry surface resistivity threshold), and the average offset of the mixes where the field-fabricated samples resulted in higher resistivity was 5.07 kΩ-cm (14% of the FDOT resistivity uncorrected for geometry surface resistivity threshold). For bulk resistivity with the RCON™ at 28-day age testing, the average offset of the mixes where the laboratory-fabricated samples resulted in higher resistivity was 6.51 kΩ-cm (22% of the FDOT resistivity uncorrected for geometry surface resistivity threshold), and the average offset of the mixes where the field-fabricated samples resulted in higher resistivity was 3.04 kΩ-cm (14% of the FDOT resistivity uncorrected for geometry surface resistivity threshold). The combinations of variables tested make it difficult to pinpoint any exact cause of the field resistivity results being higher or lower than the laboratory resistivity results. It is suspected that variations in the w/cm could have been the cause of some differences. For example, the replicate samples taken in the field for mixture 9 were much lower than those in the first batch sampled, potentially because of differences in the w/cm. Because the concrete w/cm was not measured in the field, no conclusive statements on the matter can be made, however.

4.4. Summary

Based on the resistivity values measured, the effects of different variables on resistivity can be summarized as follows:

- The resistivity results showed that frequency used was significant for the least number of mixtures and should have only a minor effect.
- Temperature control was found to be significant for only a few mixtures (7% to 20%) and RCON^{TM} (13% to 27%).
- Time of demolding was found to be significant for more mixtures with surface resistivity than bulk resistivity and should be kept within ASTM time limits for all samples.
- Limewater curing in a communal tank vs. in individual buckets was found significant in 40% of the mixtures in both surface and bulk resistivity at 28 days. Curing samples in individual buckets with new solution prepared for each set of samples is important in ensuring consistent and repeatable results.
- Moisture state during testing was found to be a significant variable. Moisture state is not difficult to control during testing. Strict compliance with the ASTM standards should be followed to ensure reliable electrical resistivity measurements.
- Significant differences in surface resistivity measurements were found between equipment used.

5. CONCLUSIONS AND RECOMMENDATIONS

5.1. Conclusions

A literature review was performed that identified six factors with the potential to induce significant variability between resistivity readings of field-fabricated samples and laboratory-fabricated samples. The factors identified were test frequency, temperature control during curing, demolding time, curing solution, sample moisture state during testing, and whether samples were made in the field or laboratory. ASTM C1067 [82] and ASTM E1169 [7] standards were used to build an experimental matrix and identify and evaluate the significance of each of the factors in the variability of resistivity readings.

It was found that sample production (laboratory or field) was the factor with the highest count of statistically significant effects across surface and bulk resistivity measurements, across equipment used, and across the 28-, 56- and 91-days testing ages studied. It was found that testing manufacturer, time of demolding, limewater curing method, and moisture state of the sample were significant for a moderate number of mixtures in inducing variability in resistivity readings between field-fabricated samples and laboratory-fabricated samples. It was also found that temperature control during initial curing and test frequency were the factors that had the fewest mixtures that showed significant differences in the resistivity readings.

There were no trends in resistivity between the laboratory- and field-made samples that held for all ages and mixtures tested. The resistivity values measured were higher in the field for some mixtures, and higher in the laboratory for other mixtures.

5.2. Recommendations

Based on the experimental results from this study, the following recommendations can be made:

- Samples should be cured in buckets with new solution and should not be mixed with samples from other mixtures. Solution should also not be reused.
- Samples should be rejected if not demolded and final curing is not started within 48 hours after fabrication.
- Samples should be kept moist during measurement.
- If used as a quality control tool, concrete samples should be cured in temperature-controlled curing boxes or insulated coolers that can maintain the temperature in the range required by ASTM C31 for standard initial curing (ASTM C31 section 10.1.2.1).

5.3. Future Research

The following topics should be considered for future research on concrete resistivity measurements:

- How to use concrete resistivity measurements in service life analysis.
- Concrete resistivity sensor use in the field.
- How w/cm variability in the field affects concrete resistivity measurements.

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Appendix A. Resistivity Readings

Table 83. Resistivity measurements mix 1

Determination	Resistivity Measurement (kΩ-cm)														
	28 Day					56 Day					91 Day				
	Surface Resistivity Giatec ASTM	Surface Resistivity Giatec at frequency	Surface Resistivity Resipod	Bulk Resistivity Giatec	Bulk Resistivity Resipod	Surface Resistivity Giatec ASTM	Surface Resistivity Giatec at frequency	Surface Resistivity Resipod	Bulk Resistivity Giatec	Bulk Resistivity Resipod	Surface Resistivity Giatec ASTM	Surface Resistivity Giatec at frequency	Surface Resistivity Resipod	Bulk Resistivity Giatec	Bulk Resistivity Resipod
Det 1	9.8	9.8	8.5	4.2	4.6	14.9	14.9	12.5	8.1	7.3	20.2	20.1	16.9	12.5	9.5
Det 2	8.9	8.8	7.7	3.2	4.5	12.8	12.7	11.2	6.9	6.6	17.4	17.2	13.8	9.2	9.1
Det 3	9.1	9.5	7.1	2.3	n/a	13.8	13.7	11.5	5.1	7.4	20.3	19.7	16.7	5.1	7.4
Det 4	9.6	9.6	8.2	4.3	4.8	14.0	14.0	12.2	9.2	7.2	19.4	19.3	15.6	11.6	9.8
Det 5	9.5	9.3	7.3	3.4	3.2	15.1	15.0	12.7	5.5	8.0	21.2	21.2	18.1	5.5	8.0
Det 6	8.9	8.9	7.0	3.1	4.8	13.7	13.7	11.3	5.5	7.2	19.5	19.5	16.5	5.5	7.1
Det 7	9.7	9.7	7.7	2.7	n/a	15.7	15.7	12.7	5.6	7.9	23.1	23.2	19.0	5.6	7.9
Det 8	11.2	11.1	9.5	4.0	5.2	16.5	16.3	13.9	7.8	7.9	21.3	21.1	18.1	11.4	9.9
Det 9	10.1	10.1	8.9	4.4	4.9	14.9	14.9	12.9	8.3	7.4	20.0	19.8	17.7	13.3	9.8
Det 10	9.3	9.1	7.7	3.2	4.5	13.0	12.9	11.1	7.3	6.6	17.7	17.5	15.0	9.1	8.9
Det 11	8.3	8.3	6.6	2.0	n/a	14.3	13.0	10.7	4.4	6.7	18.8	18.7	15.5	4.4	6.7
Det 12	9.6	9.5	8.1	4.2	4.8	14.0	13.9	12.2	9.9	7.3	19.3	19.2	15.5	11.8	10.0
Det 13	8.8	8.9	6.7	2.9	4.2	13.5	13.1	11.0	5.3	4.4	12.8	12.8	10.7	5.3	7.0
Det 14	8.6	8.5	6.8	2.6	3.6	12.8	8.6	10.7	5.3	6.5	12.8	12.8	10.7	5.3	6.5
Det 15	9.9	9.1	6.9	2.3	n/a	13.1	13.1	10.9	4.5	6.8	13.1	13.1	10.9	4.5	6.8
Det 16	10.3	10.3	8.8	3.9	5.2	15.9	15.8	13.5	8.3	7.9	21.6	21.4	18.2	11.2	10.6

Table 84. Resistivity measurements mix 2

Determination	Resistivity Measurement (kΩ-cm)														
	28 Day					56 Day					91 Day				
	Surface Resistivity Giatec ASTM	Surface Resistivity Giatec at frequency	Surface Resistivity Resipod	Bulk Resistivity Giatec	Bulk Resistivity Resipod	Surface Resistivity Giatec ASTM	Surface Resistivity Giatec at frequency	Surface Resistivity Resipod	Bulk Resistivity Giatec	Bulk Resistivity Resipod	Surface Resistivity Giatec ASTM	Surface Resistivity Giatec at frequency	Surface Resistivity Resipod	Bulk Resistivity Giatec	Bulk Resistivity Resipod
Det 1	7.0	7.0	6.2	2.9	3.3	9.8	9.8	8.5	6.2	4.6	12.3	12.2	10.0	7.9	6.0
Det 2	6.6	6.5	5.8	2.1	2.9	8.6	8.5	7.5	4.0	4.2	10.8	10.9	9.1	6.7	5.5
Det 3	6.4	6.3	5.0	0.7	2.8	8.0	8.0	6.6	2.4	2.8	10.5	10.4	8.0	3.9	5.1
Det 4	6.9	6.8	5.8	2.9	3.1	8.9	8.9	7.3	2.9	4.3	11.2	11.1	9.4	4.4	5.3
Det 5	6.3	6.4	5.3	0.9	3.2	8.3	8.2	7.3	2.6	3.2	11.4	11.4	8.8	4.3	5.5
Det 6	6.0	5.7	4.8	0.6	2.8	9.8	9.8	8.5	6.2	4.6	10.4	10.3	8.0	4.5	5.0
Det 7	6.3	6.2	5.3	0.9	2.9	7.5	7.5	6.3	1.8	3.8	10.9	10.9	8.6	4.5	5.3
Det 8	7.2	7.1	6.2	2.3	3.1	10.0	9.9	8.6	4.9	4.6	12.4	12.4	10.3	6.5	6.3
Det 9	6.9	6.9	6.2	3.0	3.2	9.5	9.8	8.5	5.6	4.6	12.2	12.1	9.9	7.6	6.0
Det 10	6.6	6.5	5.8	2.2	2.9	8.6	8.5	7.3	3.9	4.1	10.7	10.6	9.1	6.5	5.0
Det 11	6.7	6.5	5.2	0.8	3.0	8.4	8.4	7.0	2.2	4.2	11.8	11.3	9.0	4.4	5.7
Det 12	7.1	7.1	6.3	3.0	3.1	9.6	9.5	8.1	4.9	4.5	11.8	11.9	10.1	8.9	5.4
Det 13	6.4	6.4	5.2	0.9	3.3	8.6	8.5	7.3	5.3	3.1	12.1	12.0	9.3	4.8	5.8
Det 14	5.7	5.6	4.7	0.6	2.8	8.0	7.9	6.5	0.6	2.8	11.0	10.9	8.5	4.9	5.5
Det 15	6.9	7.2	5.5	1.0	3.1	9.2	9.2	7.7	1.0	3.1	12.6	12.7	9.6	4.9	5.9
Det 16	7.1	7.2	6.3	2.4	3.4	10.1	10.1	8.6	4.8	4.8	12.1	12.0	10.3	7.1	6.2

Table 85. Resistivity measurements mix 3

Determination	Resistivity Measurement (kΩ-cm)														
	28 Day					56 Day					91 Day				
	Surface Resistivity Giatec ASTM	Surface Resistivity Giatec at frequency	Surface Resistivity Resipod	Bulk Resistivity Giatec	Bulk Resistivity Resipod	Surface Resistivity Giatec ASTM	Surface Resistivity Giatec at frequency	Surface Resistivity Resipod	Bulk Resistivity Giatec	Bulk Resistivity Resipod	Surface Resistivity Giatec ASTM	Surface Resistivity Giatec at frequency	Surface Resistivity Resipod	Bulk Resistivity Giatec	Bulk Resistivity Resipod
Det 1	26.3	25.7	20.0	14.4	12.7	37.1	36.9	29.7	16.7	18.7	47.5	47.5	38.2	21.9	23.4
Det 2	27.3	27.2	21.6	13.1	13.5	36.5	36.1	30.1	16.3	18.2	43.9	43.8	37.2	20.3	22.0
Det 3	34.9	34.8	28.7	15.9	17.5	46.5	46.3	35.9	23.6	22.9	55.8	56.1	42.9	26.9	26.6
Det 4	27.0	34.7	21.0	13.5	13.0	36.8	36.8	29.7	16.2	18.3	43.7	43.8	37.7	20.3	21.9
Det 5	33.4	32.8	27.4	15.7	17.4	47.2	46.8	35.6	22.8	23.7	55.6	55.6	45.0	28.4	27.6
Det 6	31.9	31.9	27.0	15.3	16.6	41.6	42.1	33.1	21.1	21.8	48.6	49.1	42.0	25.9	25.2
Det 7	32.8	32.2	27.3	15.2	11.2	46.5	46.3	35.9	23.6	22.9	58.5	58.3	46.1	30.3	29.1
Det 8	26.5	26.2	19.7	12.7	12.7	37.0	36.9	30.0	16.5	18.8	46.2	45.8	37.1	21.4	23.0
Det 9	24.9	24.1	19.1	13.3	12.1	36.0	36.0	29.4	16.1	18.4	44.9	45.0	36.6	21.1	22.4
Det 10	26.1	25.9	20.4	13.0	13.0	35.0	34.8	28.6	15.6	17.9	42.1	41.7	35.0	19.7	22.5
Det 11	33.3	33.0	27.6	16.7	17.4	45.6	45.0	34.2	21.7	22.6	53.7	53.3	42.3	27.1	26.9
Det 12	25.8	25.9	20.7	13.9	13.1	35.0	35.4	29.3	15.8	18.0	41.9	41.8	35.4	19.6	21.5
Det 13	32.8	32.2	27.4	15.2	11.2	47.1	46.6	35.7	21.8	15.8	57.0	55.8	45.6	27.9	18.5
Det 14	32.3	32.1	26.7	14.9	15.9	43.7	43.6	34.0	21.1	21.7	52.6	53.9	43.2	26.6	26.1
Det 15	33.9	34.5	28.0	16.0	17.3	47.5	48.2	36.2	23.3	23.5	59.0	58.6	47.8	29.7	28.5
Det 16	25.1	24.8	19.6	12.6	12.8	36.3	36.0	29.9	16.7	18.8	45.4	44.9	37.4	21.5	23.2

Table 86. Resistivity measurements mix 4

Determination	Resistivity Measurement (kΩ-cm)														
	28 Day					56 Day					91 Day				
	Surface Resistivity Giatec ASTM	Surface Resistivity Giatec at frequency	Surface Resistivity Resipod	Bulk Resistivity Giatec	Bulk Resistivity Resipod	Surface Resistivity Giatec ASTM	Surface Resistivity Giatec at frequency	Surface Resistivity Resipod	Bulk Resistivity Giatec	Bulk Resistivity Resipod	Surface Resistivity Giatec ASTM	Surface Resistivity Giatec at frequency	Surface Resistivity Resipod	Bulk Resistivity Giatec	Bulk Resistivity Resipod
Det 1	25.1	24.7	20.7	10.4	12.3	28.0	27.6	23.0	12.0	14.1	30.4	30.2	25.0	14.6	15.2
Det 2	27.6	27.5	22.5	10.7	12.4	30.4	30.2	26.1	12.5	14.7	32.9	33.0	27.4	14.4	15.6
Det 3	26.6	26.6	20.8	12.2	13.7	33.8	33.6	26.8	17.0	17.2	34.1	33.6	26.4	18.3	17.0
Det 4	24.2	23.9	20.6	10.3	12.1	27.6	27.4	22.9	12.1	14.1	28.7	28.9	24.5	14.2	14.9
Det 5	28.9	28.9	22.9	13.5	14.8	38.2	38.6	30.9	19.4	19.5	38.2	37.4	28.3	19.2	18.9
Det 6	26.1	26.5	15.2	12.7	13.7	34.0	33.8	27.0	18.5	17.7	34.1	33.9	24.5	18.4	16.8
Det 7	32.1	33.0	24.6	14.5	15.4	41.1	41.2	32.0	21.1	20.1	41.5	41.8	31.7	22.1	19.7
Det 8	26.5	26.2	21.2	10.8	10.6	28.7	29.2	24.0	12.4	14.6	31.9	32.4	25.4	15.0	15.7
Det 9	25.2	24.1	21.1	10.7	12.5	27.1	27.0	23.2	12.2	14.4	30.8	30.8	25.1	14.7	15.4
Det 10	26.7	26.4	22.2	10.7	12.6	29.1	29.4	25.0	12.9	15.0	30.8	30.6	25.7	14.5	15.5
Det 11	25.6	25.7	20.4	11.8	13.2	33.2	32.9	27.1	17.2	17.4	34.1	33.7	27.2	17.8	16.8
Det 12	27.3	27.2	22.3	10.7	12.7	30.9	31.0	26.3	12.6	15.0	31.3	31.4	26.3	15.1	15.7
Det 13	28.3	28.8	21.9	12.9	14.0	37.7	37.2	29.8	18.7	18.8	37.7	37.4	28.3	18.8	18.1
Det 14	24.1	23.8	19.3	11.5	12.3	32.3	32.0	25.7	17.0	16.2	32.4	32.2	24.9	17.3	15.6
Det 15	29.5	29.8	22.7	13.5	14.5	38.1	38.0	30.2	19.8	19.1	38.6	38.6	29.8	20.6	18.2
Det 16	25.9	25.7	21.5	10.7	12.5	29.4	29.2	23.8	12.6	14.8	31.3	31.6	25.6	14.7	15.9

Table 87. Resistivity measurements mix 5

Determination	Resistivity Measurement (kΩ-cm)														
	28 Day					56 Day					91 Day				
	Surface Resistivity Giatec ASTM	Surface Resistivity Giatec at frequency	Surface Resistivity Resipod	Bulk Resistivity Giatec	Bulk Resistivity Resipod	Surface Resistivity Giatec ASTM	Surface Resistivity Giatec at frequency	Surface Resistivity Resipod	Bulk Resistivity Giatec	Bulk Resistivity Resipod	Surface Resistivity Giatec ASTM	Surface Resistivity Giatec at frequency	Surface Resistivity Resipod	Bulk Resistivity Giatec	Bulk Resistivity Resipod
Det 1	30.3	30.6	25.3	11.9	13.9	38.8	39.0	31.4	16.5	18.4	42.9	42.8	34.7	19.4	19.8
Det 2	26.4	30.6	25.3	11.4	13.9	33.4	33.0	28.6	15.3	17.2	36.8	36.4	30.6	17.6	18.3
Det 3	27.3	27.5	21.2	13.3	13.8	34.9	34.6	27.0	18.2	17.5	37.0	36.8	27.8	19.2	16.7
Det 4	30.7	30.8	26.1	12.6	14.1	37.3	37.6	32.2	16.7	18.6	40.8	41.1	34.1	19.2	19.7
Det 5	32.2	32.2	25.0	14.9	15.4	38.8	44.2	30.4	19.2	18.1	40.0	39.5	31.4	19.0	17.2
Det 6	28.0	28.1	22.3	14.4	13.8	34.6	34.3	28.5	18.4	17.4	36.0	36.0	29.3	19.8	16.4
Det 7	31.5	31.9	25.1	15.6	15.2	40.8	40.8	31.7	20.7	19.1	41.1	41.3	31.7	21.6	18.2
Det 8	33.0	32.6	27.5	13.5	15.2	41.4	41.2	33.1	17.9	19.9	44.5	44.4	35.7	20.3	21.2
Det 9	27.3	27.5	23.2	11.5	13.3	34.7	32.9	29.4	16.0	17.9	37.6	38.4	31.8	18.9	19.3
Det 10	25.4	25.4	22.6	10.8	12.6	32.5	33.3	28.1	14.6	16.9	36.6	36.4	31.1	16.7	17.9
Det 11	29.7	29.5	23.5	14.5	15.1	36.0	36.1	29.3	19.0	18.6	37.6	39.3	29.0	19.7	17.7
Det 12	30.8	31.2	26.3	13.5	15.0	38.1	38.6	32.3	16.8	18.9	41.5	41.8	34.0	20.1	20.7
Det 13	32.1	32.2	25.1	15.6	16.2	39.9	39.6	30.7	19.8	19.6	39.1	39.4	32.9	21.0	18.2
Det 14	27.6	27.9	22.7	14.4	14.5	37.0	36.8	28.3	18.9	18.0	37.3	37.2	30.3	20.9	15.9
Det 15	35.1	35.1	27.0	17.4	17.4	43.1	43.7	33.7	21.6	20.7	43.5	43.5	32.3	22.1	19.9
Det 16	31.9	31.6	26.0	13.1	14.9	40.7	40.5	33.2	17.2	19.7	43.1	42.4	35.0	20.1	20.9

Table 88. Resistivity measurements mix 6

Determination	Resistivity Measurement (kΩ-cm)														
	28 Day					56 Day					91 Day				
	Surface Resistivity Giatec ASTM	Surface Resistivity Giatec at frequency	Surface Resistivity Resipod	Bulk Resistivity Giatec	Bulk Resistivity Resipod	Surface Resistivity Giatec ASTM	Surface Resistivity Giatec at frequency	Surface Resistivity Resipod	Bulk Resistivity Giatec	Bulk Resistivity Resipod	Surface Resistivity Giatec ASTM	Surface Resistivity Giatec at frequency	Surface Resistivity Resipod	Bulk Resistivity Giatec	Bulk Resistivity Resipod
Det 1	25.9	25.4	19.9	16.1	11.1	28.8	28.9	22.7	16.1	13.9	28.8	28.9	23.1	17.3	14.4
Det 2	25.7	25.7	19.9	13.2	11.5	27.4	26.7	21.4	13.6	13.4	27.7	27.8	22.8	14.8	14.5
Det 3	22.4	22.4	17.4	10.2	10.6	30.2	30.0	22.5	14.9	14.3	30.2	29.9	24.0	16.3	15.3
Det 4	25.4	25.0	20.0	13.0	11.5	26.8	26.4	21.5	14.6	13.7	28.5	28.4	23.4	15.2	14.8
Det 5	24.3	23.8	19.0	11.4	11.9	31.4	30.0	22.5	14.9	14.3	31.2	31.4	24.9	16.8	16.0
Det 6	21.3	21.1	16.7	10.8	10.7	27.9	28.2	20.9	15.4	14.4	27.6	28.4	22.8	17.2	15.2
Det 7	24.4	24.2	19.5	12.3	11.9	32.2	31.6	24.5	16.8	15.8	32.0	32.2	25.5	18.8	16.4
Det 8	27.0	27.0	20.6	14.0	11.9	30.2	30.0	23.1	14.9	15.0	29.6	29.6	23.7	16.0	15.5
Det 9	25.4	25.2	19.3	13.3	11.2	28.5	28.7	22.0	15.1	13.9	28.7	29.1	22.4	15.4	14.6
Det 10	23.8	23.6	19.1	12.3	11.1	26.5	26.2	21.6	13.7	13.8	29.2	28.9	23.2	16.2	15.2
Det 11	21.9	21.9	17.6	10.9	11.3	29.2	28.2	22.4	15.1	14.8	29.8	29.2	23.6	16.3	15.6
Det 12	25.5	25.2	19.6	13.3	11.6	27.5	28.4	21.4	14.4	14.3	29.3	29.2	23.2	16.2	15.5
Det 13	22.9	22.8	18.5	11.0	11.5	31.4	31.5	22.2	15.2	14.9	28.9	28.9	24.2	16.2	15.8
Det 14	22.0	22.0	17.0	10.7	10.7	29.1	29.2	21.2	15.4	14.3	28.9	29.1	23.0	16.1	15.2
Det 15	24.4	24.3	19.1	12.1	11.6	32.3	30.9	24.8	17.8	15.4	31.8	31.0	25.1	18.0	15.9
Det 16	27.1	27.1	21.5	14.4	12.1	30.8	30.1	24.3	16.6	14.4	30.9	30.8	25.2	16.6	15.1

Table 89. Resistivity measurements mix 7

Determination	Resistivity Measurement (kΩ-cm)														
	28 Day					56 Day					91 Day				
	Surface Resistivity Giatec ASTM	Surface Resistivity Giatec at frequency	Surface Resistivity Resipod	Bulk Resistivity Giatec	Bulk Resistivity Resipod	Surface Resistivity Giatec ASTM	Surface Resistivity Giatec at frequency	Surface Resistivity Resipod	Bulk Resistivity Giatec	Bulk Resistivity Resipod	Surface Resistivity Giatec ASTM	Surface Resistivity Giatec at frequency	Surface Resistivity Resipod	Bulk Resistivity Giatec	Bulk Resistivity Resipod
Det 1	8.3	7.9	6.9	2.8	2.0	10.0	10.6	8.1	4.0	4.6	13.8	13.7	11.5	6.0	7.3
Det 2	8.1	8.4	6.0	2.8	3.1	10.6	10.2	8.8	4.4	5.2	13.4	13.4	13.4	5.9	7.2
Det 3	7.4	7.0	5.4	2.0	3.0	10.2	10.0	8.0	3.8	4.6	14.0	13.9	11.7	6.1	6.8
Det 4	7.5	7.4	5.8	2.1	3.0	10.8	10.7	9.0	4.1	5.1	14.5	14.3	11.8	6.4	7.2
Det 5	6.8	6.4	5.2	2.2	2.9	9.9	9.7	8.2	3.6	3.3	12.5	12.4	10.6	4.2	6.3
Det 6	4.5	6.7	4.1	2.9	2.0	10.3	9.7	8.2	3.5	2.8	12.9	12.9	11.1	4.0	6.1
Det 7	5.9	7.9	5.3	3.3	2.9	10.6	10.1	8.1	3.8	3.0	14.3	14.3	11.7	4.9	6.9
Det 8	7.7	7.5	6.7	2.6	2.6	11.6	11.6	8.4	4.8	4.6	13.8	13.7	9.9	6.0	7.1
Det 9	7.4	7.6	6.2	2.4	3.0	10.2	9.3	7.7	3.3	4.4	13.3	13.3	11.0	5.0	7.2
Det 10	7.5	7.4	5.9	2.1	2.9	10.4	10.3	8.6	3.9	4.9	13.4	13.4	11.2	5.8	7.0
Det 11	6.6	6.4	5.0	2.0	2.7	9.8	9.7	7.6	3.6	4.5	13.9	13.8	12.2	4.8	5.3
Det 12	7.0	6.9	5.6	1.8	2.9	10.1	10.0	8.2	3.7	4.7	13.0	13.0	10.7	5.5	6.8
Det 13	6.6	6.4	5.0	2.1	2.7	9.9	9.8	8.0	3.6	4.5	14.0	13.9	11.9	4.6	6.7
Det 14	6.7	6.0	4.7	2.3	2.6	9.2	9.1	7.5	3.2	4.2	12.8	12.8	11.5	4.3	6.3
Det 15	6.3	6.3	4.9	2.7	2.8	10.9	9.9	7.6	3.6	4.5	14.2	14.3	11.9	5.1	7.1
Det 16	8.2	8.0	6.5	2.4	2.9	11.8	11.7	8.5	5.0	4.7	15.1	14.7	12.5	6.8	7.5

Table 90. Resistivity measurements mix 8

Determination	Resistivity Measurement (kΩ-cm)														
	28 Day					56 Day					91 Day				
	Surface Resistivity Giatec ASTM	Surface Resistivity Giatec at frequency	Surface Resistivity Resipod	Bulk Resistivity Giatec	Bulk Resistivity Resipod	Surface Resistivity Giatec ASTM	Surface Resistivity Giatec at frequency	Surface Resistivity Resipod	Bulk Resistivity Giatec	Bulk Resistivity Resipod	Surface Resistivity Giatec ASTM	Surface Resistivity Giatec at frequency	Surface Resistivity Resipod	Bulk Resistivity Giatec	Bulk Resistivity Resipod
Det 1	54.1	53.7	45.0	26.8	26.6	71.5	71.0	59.9	36.3	34.4	79.4	78.0	65.4	41.9	39.4
Det 2	46.7	47.2	38.3	22.7	22.7	62.3	62.1	51.5	31.5	31.1	68.7	68.8	61.2	33.6	36.0
Det 3	43.8	43.0	32.5	21.4	20.5	56.8	56.1	43.2	29.0	26.9	63.1	62.0	52.1	30.3	31.9
Det 4	48.4	49.1	40.4	25.3	24.5	63.2	63.3	52.8	34.3	32.6	69.4	69.6	61.7	38.6	36.9
Det 5	41.2	40.5	32.5	20.1	19.9	50.3	50.1	42.1	27.1	26.1	58.5	57.9	50.1	28.9	30.7
Det 6	43.0	42.7	33.7	21.4	20.1	52.8	52.6	44.0	29.1	26.8	59.9	59.8	52.3	29.9	31.4
Det 7	45.3	45.1	34.5	22.3	20.5	53.9	53.7	42.6	29.8	27.1	62.6	62.1	52.6	29.9	31.6
Det 8	54.6	54.4	43.7	26.7	26.6	71.0	70.1	59.6	35.6	35.7	81.7	80.7	68.9	41.9	41.3
Det 9	53.1	53.1	43.8	26.2	25.7	68.4	68.4	58.2	35.0	33.2	78.8	78.8	66.4	40.1	38.0
Det 10	45.1	45.2	38.5	22.2	22.6	63.5	63.1	51.5	30.7	30.3	64.8	65.5	59.0	34.5	34.2
Det 11	42.5	42.0	33.1	21.4	21.2	55.7	55.0	41.8	28.6	27.1	62.7	62.1	52.8	30.4	32.6
Det 12	48.0	48.9	41.5	25.4	23.6	68.2	68.0	55.6	34.1	33.2	72.1	72.8	63.8	38.7	36.9
Det 13	41.3	41.1	32.7	19.8	19.7	49.1	48.9	41.3	26.5	25.5	58.4	58.0	49.6	27.9	29.7
Det 14	40.8	40.8	32.5	21.7	20.3	50.8	50.5	42.3	29.4	26.5	59.3	59.1	50.1	31.9	31.1
Det 15	44.7	43.7	34.6	21.7	20.6	54.2	54.1	42.6	29.9	26.3	61.0	60.4	52.4	31.7	31.6
Det 16	55.0	54.3	44.4	26.0	26.6	70.7	69.8	57.4	35.9	35.1	83.1	83.0	70.3	41.8	41.4

Table 91. Resistivity measurements mix 9

Determination	Resistivity Measurement (kΩ-cm)														
	28 Day					56 Day					91 Day				
	Surface Resistivity Giatec ASTM	Surface Resistivity Giatec at frequency	Surface Resistivity Resipod	Bulk Resistivity Giatec	Bulk Resistivity Resipod	Surface Resistivity Giatec ASTM	Surface Resistivity Giatec at frequency	Surface Resistivity Resipod	Bulk Resistivity Giatec	Bulk Resistivity Resipod	Surface Resistivity Giatec ASTM	Surface Resistivity Giatec at frequency	Surface Resistivity Resipod	Bulk Resistivity Giatec	Bulk Resistivity Resipod
Det 1	40.3	40.2	33.1	21.0	21.5	47.1	46.8	37.6	26.8	25.5	49.3	49.3	40.9	27.9	26.8
Det 2	36.4	37.0	30.8	18.2	19.8	42.3	42.4	34.2	22.6	22.2	42.7	45.4	39.2	23.9	24.2
Det 3	35.5	35.8	29.6	16.1	18.1	42.7	42.8	34.5	19.6	21.6	48.3	47.3	38.9	24.9	24.0
Det 4	39.8	40.4	32.0	19.7	20.4	42.9	44.0	35.8	25.0	23.5	48.1	49.3	40.3	26.1	25.4
Det 5	39.0	39.2	31.8	18.4	20.4	45.0	45.3	37.2	21.4	23.4	52.1	51.3	42.2	27.0	26.2
Det 6	28.0	28.4	25.7	14.6	16.6	33.1	33.4	29.8	17.6	19.5	42.1	40.6	35.3	24.9	22.1
Det 7	38.4	38.2	32.8	18.1	19.9	43.6	42.9	36.1	21.1	22.9	49.0	49.1	41.1	27.3	25.2
Det 8	41.9	41.4	34.2	20.2	21.2	50.0	49.5	39.5	26.2	25.6	51.7	52.1	43.4	27.0	27.0
Det 9	43.4	43.4	35.0	21.6	22.4	51.0	50.3	40.1	28.7	26.4	57.5	53.0	43.4	30.6	27.1
Det 10	36.5	35.8	30.7	18.0	19.3	40.0	39.7	33.7	22.5	21.9	43.0	43.8	38.4	24.1	23.9
Det 11	23.3	23.1	20.1	10.5	12.7	27.3	27.2	21.9	12.1	14.5	30.4	31.6	24.9	15.7	15.5
Det 12	36.2	35.7	30.6	18.7	19.6	41.2	41.4	34.4	24.1	22.2	47.4	43.2	39.3	25.5	24.7
Det 13	18.5	18.9	17.3	9.9	12.4	19.5	19.8	18.3	10.3	12.7	23.3	22.2	21.2	14.9	14.1
Det 14	28.9	28.6	25.9	15.4	18.1	34.4	34.6	29.4	17.7	19.6	40.8	40.2	34.3	25.1	23.5
Det 15	28.4	28.2	24.2	14.1	16.3	30.0	29.9	25.4	15.0	17.1	33.7	31.9	28.4	20.2	18.4
Det 16	40.4	40.0	33.5	20.2	21.5	48.6	47.9	39.3	26.8	25.9	53.6	51.1	43.7	27.3	27.0

Table 92. Resistivity measurements mix 10

Determination	Resistivity Measurement (kΩ-cm)														
	28 Day					56 Day					91 Day				
	Surface Resistivity Giatec ASTM	Surface Resistivity Giatec at frequency	Surface Resistivity Resipod	Bulk Resistivity Giatec	Bulk Resistivity Resipod	Surface Resistivity Giatec ASTM	Surface Resistivity Giatec at frequency	Surface Resistivity Resipod	Bulk Resistivity Giatec	Bulk Resistivity Resipod	Surface Resistivity Giatec ASTM	Surface Resistivity Giatec at frequency	Surface Resistivity Resipod	Bulk Resistivity Giatec	Bulk Resistivity Resipod
Det 1	21.3	21.3	17.6	9.4	10.4	27.9	27.9	21.2	14.7	13.6	30.6	30.4	25.3	16.0	15.0
Det 2	19.4	19.5	16.1	8.2	9.7	26.4	27.0	20.9	13.2	13.0	29.7	29.8	24.6	14.4	14.3
Det 3	18.5	18.5	14.8	7.1	9.5	24.9	24.5	20.2	11.2	13.1	26.9	26.7	22.1	13.2	13.9
Det 4	19.9	20.0	16.4	9.2	10.3	26.8	26.9	21.3	15.7	13.4	30.4	30.6	25.4	18.0	15.0
Det 5	21.5	21.5	17.9	8.6	10.9	26.0	26.3	21.5	11.4	13.2	28.7	28.7	23.2	13.7	14.3
Det 6	18.8	18.7	16.0	7.6	9.8	25.1	24.3	20.1	11.2	12.8	26.8	26.6	21.5	14.0	14.0
Det 7	20.9	20.8	17.0	8.6	10.9	26.9	26.9	22.1	12.8	14.0	27.7	28.0	22.8	14.6	14.7
Det 8	22.2	22.0	18.3	9.6	11.2	29.2	29.4	22.4	14.6	14.3	30.6	30.2	25.4	15.6	15.7
Det 9	22.1	21.9	18.0	10.0	11.1	28.7	29.4	22.5	15.7	14.0	29.3	29.0	26.4	16.3	15.2
Det 10	19.1	19.0	16.2	8.6	9.9	24.9	24.6	20.6	13.4	13.0	27.9	27.5	23.4	14.9	13.5
Det 11	17.6	17.3	14.0	6.4	8.8	24.9	24.2	20.3	10.7	12.6	27.2	27.1	22.6	13.0	13.6
Det 12	19.6	19.8	16.3	9.5	10.1	25.6	25.9	21.0	15.3	13.0	29.1	28.9	24.4	17.3	14.7
Det 13	20.8	20.8	17.3	8.3	10.7	26.5	26.5	21.0	11.5	13.3	29.5	29.0	23.5	13.8	14.3
Det 14	19.3	19.3	16.3	7.6	9.9	26.0	26.1	21.3	11.8	13.3	28.7	28.9	23.0	14.5	14.5
Det 15	20.5	20.5	17.3	8.3	10.7	26.8	26.9	22.0	12.4	13.8	28.5	28.4	23.4	14.5	14.6
Det 16	22.7	22.5	18.4	10.3	11.7	30.1	29.8	22.9	15.3	14.8	32.4	32.2	26.0	16.2	16.2

Table 93. Resistivity measurements mix 11

Determination	Resistivity Measurement (kΩ-cm)														
	28 Day					56 Day					91 Day				
	Surface Resistivity Giatec ASTM	Surface Resistivity Giatec at frequency	Surface Resistivity Resipod	Bulk Resistivity Giatec	Bulk Resistivity Resipod	Surface Resistivity Giatec ASTM	Surface Resistivity Giatec at frequency	Surface Resistivity Resipod	Bulk Resistivity Giatec	Bulk Resistivity Resipod	Surface Resistivity Giatec ASTM	Surface Resistivity Giatec at frequency	Surface Resistivity Resipod	Bulk Resistivity Giatec	Bulk Resistivity Resipod
Det 1	14.0	14.0	12.0	6.6	7.8	17.1	17.0	14.1	9.8	9.4	18.4	18.3	15.2	13.7	11.2
Det 2	13.3	13.4	12.1	5.1	6.6	16.2	16.1	14.1	7.7	10.1	18.1	18.0	15.7	9.6	9.2
Det 3	16.6	16.4	14.2	6.0	8.4	19.2	19.0	15.7	7.8	9.5	20.8	20.7	17.2	11.2	10.6
Det 4	13.9	14.0	12.8	6.8	7.7	18.1	18.0	15.1	9.9	8.3	18.8	18.8	16.5	13.5	10.0
Det 5	16.4	16.1	13.7	6.8	9.2	18.7	18.6	15.2	8.5	10.1	20.8	20.6	17.2	12.6	11.3
Det 6	16.6	16.5	13.4	6.6	8.8	18.3	18.3	15.2	8.5	9.8	20.9	20.8	17.0	14.6	11.3
Det 7	16.4	16.4	13.4	6.5	8.8	18.7	18.6	15.2	8.2	9.6	20.9	20.9	16.8	14.1	10.9
Det 8	16.4	16.5	13.8	7.0	8.6	19.3	19.8	16.2	10.3	10.4	22.1	21.6	18.2	13.2	12.6
Det 9	14.7	14.6	12.6	6.2	7.7	17.8	18.1	14.8	9.7	9.3	18.4	18.3	15.2	13.7	11.2
Det 10	12.8	12.6	11.2	5.1	6.8	15.3	15.2	13.4	8.3	8.2	19.8	19.8	16.9	13.6	11.0
Det 11	19.5	19.4	15.2	7.4	6.5	22.2	22.0	17.9	9.5	11.1	24.9	24.1	20.4	13.6	12.3
Det 12	15.0	15.0	13.1	6.5	7.7	18.0	18.0	15.8	9.8	11.4	19.3	19.3	15.9	11.7	10.2
Det 13	19.3	18.9	15.6	7.9	10.4	22.3	22.1	17.7	10.0	11.2	24.2	22.8	19.9	14.0	12.5
Det 14	19.3	19.0	15.6	8.1	10.4	21.7	21.8	18.0	10.5	11.6	24.3	24.1	20.2	17.1	12.9
Det 15	19.1	19.1	15.4	8.2	10.5	22.5	22.1	17.8	10.4	11.4	23.9	23.6	19.0	16.5	12.5
Det 16	15.9	15.8	13.0	6.7	8.3	18.5	18.4	14.8	9.8	11.9	20.8	20.5	16.6	12.3	12.0

Table 94. Resistivity measurements mix 12

Determination	Resistivity Measurement (kΩ-cm)														
	28 Day					56 Day					91 Day				
	Surface Resistivity Giatec ASTM	Surface Resistivity Giatec at frequency	Surface Resistivity Resipod	Bulk Resistivity Giatec	Bulk Resistivity Resipod	Surface Resistivity Giatec ASTM	Surface Resistivity Giatec at frequency	Surface Resistivity Resipod	Bulk Resistivity Giatec	Bulk Resistivity Resipod	Surface Resistivity Giatec ASTM	Surface Resistivity Giatec at frequency	Surface Resistivity Resipod	Bulk Resistivity Giatec	Bulk Resistivity Resipod
Det 1	21.1	21.0	17.4	9.4	10.8	26.1	26.4	22.2	15.1	13.4	28.1	28.3	24.0	17.4	14.8
Det 2	18.3	18.3	15.3	7.8	9.4	24.1	24.1	20.2	12.0	11.7	25.2	25.3	20.3	13.0	12.8
Det 3	24.4	24.1	19.6	10.2	12.4	29.7	29.6	23.1	13.5	14.9	31.1	31.0	25.1	16.1	16.0
Det 4	19.9	19.9	16.4	9.7	10.8	25.6	25.9	22.4	15.0	13.9	27.7	27.4	22.9	16.4	14.8
Det 5	25.6	25.8	21.0	11.4	13.5	29.9	29.6	24.3	14.4	15.8	31.8	31.7	26.2	16.9	16.6
Det 6	24.1	24.2	19.9	10.9	12.8	28.6	28.9	23.1	14.1	15.4	30.3	30.0	24.5	17.1	16.0
Det 7	25.6	25.3	21.0	11.2	13.3	29.9	30.2	24.7	14.8	15.7	32.1	32.3	26.4	17.6	16.8
Det 8	24.0	23.8	19.7	10.3	11.9	29.1	29.2	25.0	15.1	15.2	32.5	32.3	27.4	17.7	16.8
Det 9	23.9	23.7	20.3	11.6	12.8	29.6	29.4	25.1	16.9	15.8	32.7	32.4	27.8	20.3	18.0
Det 10	21.3	21.3	17.4	9.3	10.8	27.7	27.7	22.9	13.9	13.9	29.1	28.9	23.4	15.1	14.6
Det 11	23.5	23.4	19.8	10.0	12.3	28.2	28.4	23.7	13.4	14.8	31.6	31.1	25.4	16.1	15.9
Det 12	23.5	23.3	19.5	10.9	11.9	31.4	31.2	26.0	16.5	15.3	32.9	32.8	26.7	18.1	16.2
Det 13	25.8	25.7	21.2	11.2	13.3	29.5	29.6	24.3	14.2	15.4	32.2	31.9	25.9	16.9	16.4
Det 14	24.7	24.6	20.6	11.2	13.0	29.5	29.8	23.9	14.5	15.6	31.3	30.8	25.1	17.5	16.3
Det 15	25.6	25.4	20.7	10.5	12.6	29.5	29.1	24.1	14.0	14.9	31.9	31.5	26.0	16.8	15.7
Det 16	26.5	26.5	20.8	11.8	13.5	31.6	31.2	26.2	16.8	16.6	34.6	34.9	29.0	19.2	18.4

Table 95. Resistivity measurements mix 13

Determination	Resistivity Measurement (kΩ-cm)														
	28 Day					56 Day					91 Day				
	Surface Resistivity Giatec ASTM	Surface Resistivity Giatec at frequency	Surface Resistivity Resipod	Bulk Resistivity Giatec	Bulk Resistivity Resipod	Surface Resistivity Giatec ASTM	Surface Resistivity Giatec at frequency	Surface Resistivity Resipod	Bulk Resistivity Giatec	Bulk Resistivity Resipod	Surface Resistivity Giatec ASTM	Surface Resistivity Giatec at frequency	Surface Resistivity Resipod	Bulk Resistivity Giatec	Bulk Resistivity Resipod
Det 1	7.0	7.0	6.0	3.0	3.4	8.4	8.2	6.9	5.0	4.0	8.9	8.8	8.0	7.2	5.4
Det 2	6.1	6.0	5.3	1.9	3.2	7.0	6.9	6.2	3.8	3.3	7.7	7.7	6.7	4.2	4.1
Det 3	11.5	11.4	9.8	3.7	5.8	14.4	14.3	12.2	5.8	7.0	15.5	15.4	13.3	7.4	7.6
Det 4	6.2	6.1	5.6	2.8	3.3	7.3	7.3	6.5	5.0	3.5	8.3	8.3	6.9	5.6	4.3
Det 5	11.2	11.1	9.4	3.7	5.8	13.3	13.2	11.3	5.8	6.6	14.3	14.1	12.0	7.1	7.4
Det 6	11.9	12.0	9.9	4.5	6.3	13.8	13.8	11.9	7.2	7.3	15.3	15.3	12.9	8.6	8.4
Det 7	11.2	11.2	9.6	3.9	5.7	14.0	13.9	11.6	6.4	6.8	14.6	14.5	12.3	7.8	7.2
Det 8	6.9	6.9	5.8	2.2	3.5	8.2	8.2	7.0	4.1	4.4	9.5	9.5	7.5	6.4	5.8
Det 9	6.7	6.7	5.9	2.7	3.5	7.7	7.6	6.8	4.9	4.2	8.7	8.7	7.8	8.0	5.7
Det 10	6.4	6.4	5.8	1.8	3.1	7.6	7.5	6.9	3.9	3.7	8.6	8.6	7.3	5.2	4.1
Det 11	10.4	10.3	8.9	3.3	5.3	13.0	12.9	11.0	5.3	6.6	14.1	14.0	11.9	6.7	7.0
Det 12	6.9	6.8	6.0	2.8	3.2	7.9	8.0	6.9	5.5	4.0	8.7	8.6	7.5	5.6	4.5
Det 13	10.6	10.5	8.9	3.3	5.4	12.4	12.4	10.7	5.4	6.5	13.4	13.3	11.5	6.6	6.9
Det 14	11.3	11.2	9.7	3.9	5.7	13.5	13.5	11.8	6.6	6.7	14.5	14.4	12.5	7.8	7.4
Det 15	10.4	10.4	8.9	3.5	5.3	12.6	12.6	10.8	6.0	6.1	13.9	13.9	11.5	7.2	6.7
Det 16	7.0	7.0	6.2	2.3	3.6	8.4	8.3	7.1	3.9	4.6	9.0	8.9	7.9	6.2	5.9

Table 96. Resistivity measurements mix 14

Determination	Resistivity Measurement (kΩ-cm)														
	28 Day					56 Day					91 Day				
	Surface Resistivity Giatec ASTM	Surface Resistivity Giatec at frequency	Surface Resistivity Resipod	Bulk Resistivity Giatec	Bulk Resistivity Resipod	Surface Resistivity Giatec ASTM	Surface Resistivity Giatec at frequency	Surface Resistivity Resipod	Bulk Resistivity Giatec	Bulk Resistivity Resipod	Surface Resistivity Giatec ASTM	Surface Resistivity Giatec at frequency	Surface Resistivity Resipod	Bulk Resistivity Giatec	Bulk Resistivity Resipod
Det 1	33.7	33.8	27.4	17.7	16.7	41.9	41.5	33.7	22.8	20.9	48.1	47.6	40.8	26.5	23.5
Det 2	31.4	31.8	26.8	15.0	15.1	37.8	37.6	32.8	19.3	18.9	45.0	46.0	38.1	22.2	22.3
Det 3	34.7	34.8	29.2	16.9	17.7	44.1	44.2	34.9	22.5	22.7	47.4	47.4	38.4	25.2	24.5
Det 4	32.2	32.2	27.0	17.5	15.9	39.0	39.1	32.7	22.5	19.8	43.4	43.6	38.3	24.8	23.0
Det 5	37.9	38.2	30.9	17.2	18.6	44.0	43.8	37.7	22.3	21.2	49.3	48.6	40.2	25.1	24.7
Det 6	35.7	35.6	28.9	17.7	18.4	42.2	41.2	35.4	24.6	22.4	48.5	48.3	41.0	27.2	25.2
Det 7	37.3	37.0	30.3	18.6	19.1	44.0	44.2	34.9	24.6	23.1	48.2	47.8	38.0	26.7	25.1
Det 8	36.7	36.8	29.5	17.9	18.0	44.3	44.8	37.3	23.2	22.4	50.9	50.5	45.2	26.7	25.7
Det 9	31.6	31.6	25.6	18.0	16.7	39.0	38.4	31.7	23.2	20.9	44.1	44.6	36.8	26.7	23.9
Det 10	29.4	29.4	23.5	14.5	14.3	35.4	35.5	28.9	18.6	17.9	40.4	40.0	34.2	21.1	20.9
Det 11	35.7	36.0	31.0	17.1	18.3	47.0	46.8	38.9	23.6	23.4	51.3	51.1	42.1	26.8	26.0
Det 12	32.6	32.6	27.1	17.0	15.7	39.8	40.0	33.3	21.4	19.3	45.3	45.3	39.7	24.6	22.6
Det 13	37.6	37.7	30.8	18.8	19.1	44.5	43.8	37.8	23.9	23.1	49.7	48.9	41.1	26.7	25.9
Det 14	34.9	35.2	28.5	17.8	18.0	42.2	43.0	34.8	24.4	22.1	47.1	46.8	38.4	27.2	25.3
Det 15	36.8	36.6	31.1	18.1	18.5	46.4	45.6	37.7	22.9	22.1	48.3	49.7	38.1	26.0	23.9
Det 16	33.3	33.2	28.4	17.8	16.9	43.4	43.0	34.9	22.3	21.2	51.4	51.2	42.2	25.6	24.1

Table 97. Resistivity measurements mix 15

Determination	Resistivity Measurement (kΩ-cm)														
	28 Day					56 Day					91 Day				
	Surface Resistivity Giatec ASTM	Surface Resistivity Giatec at frequency	Surface Resistivity Resipod	Bulk Resistivity Giatec	Bulk Resistivity Resipod	Surface Resistivity Giatec ASTM	Surface Resistivity Giatec at frequency	Surface Resistivity Resipod	Bulk Resistivity Giatec	Bulk Resistivity Resipod	Surface Resistivity Giatec ASTM	Surface Resistivity Giatec at frequency	Surface Resistivity Resipod	Bulk Resistivity Giatec	Bulk Resistivity Resipod
Det 1	8.5	8.5	7.1	5.1	3.8	12.5	12.5	11.2	8.1	7.5	16.0	16.0	14.1	12.3	8.8
Det 2	7.5	7.4	6.3	3.1	3.5	11.2	11.0	9.9	5.6	5.6	13.8	13.7	11.8	7.5	7.2
Det 3	5.9	6.0	5.9	3.6	1.6	8.8	8.8	7.5	4.2	4.2	12.2	12.1	10.4	6.8	5.8
Det 4	7.9	7.9	6.8	3.6	3.6	12.3	12.2	10.8	6.9	5.9	15.5	15.5	13.2	9.3	7.5
Det 5	6.5	6.4	5.7	4.1	2.8	9.6	9.6	8.2	5.1	5.2	12.7	12.6	10.9	7.4	6.8
Det 6	6.5	6.5	5.7	5.1	3.3	9.8	9.8	8.2	6.3	5.1	12.9	12.9	11.1	9.5	6.9
Det 7	6.3	6.3	5.9	5.0	2.9	9.4	9.4	8.1	5.2	4.4	12.9	12.8	11.4	8.7	6.1
Det 8	8.6	8.5	7.4	4.2	4.3	13.3	13.3	12.0	7.4	7.9	16.9	16.8	15.0	10.6	10.7
Det 9	8.3	8.3	6.9	4.8	3.5	12.3	12.2	11.1	8.4	7.4	15.7	15.5	13.8	13.0	11.2
Det 10	7.2	7.1	6.3	2.8	3.0	11.5	11.4	10.0	5.6	5.6	13.8	13.8	11.9	7.3	7.0
Det 11	5.6	5.6	4.9	2.9	2.7	8.9	8.7	7.7	4.3	4.4	12.7	12.6	11.1	7.2	6.2
Det 12	8.0	8.0	6.6	3.9	3.5	12.0	12.0	10.3	7.0	5.7	14.8	14.8	12.4	9.3	7.3
Det 13	6.4	6.4	5.7	3.3	2.8	10.3	10.2	8.9	5.1	5.2	14.2	14.1	11.9	8.1	7.0
Det 14	6.4	6.4	5.7	5.2	2.6	10.4	10.3	8.8	6.3	5.3	14.0	14.0	11.8	10.1	7.3
Det 15	5.9	5.9	5.2	5.0	2.9	9.2	9.1	7.8	5.6	4.5	13.1	13.0	11.2	9.3	6.2
Det 16	8.7	8.6	7.3	3.9	3.8	13.4	13.3	11.8	7.4	7.7	16.8	16.6	14.8	10.6	11.0