

Freeze-Thaw, Surface Resistivity, and High Temperature Performance of Local UHPC

A Thesis Presented for the
Master of Science
Degree
The University of Tennessee, Knoxville

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December 2024

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Acknowledgements

First and foremost, thank you God. This has been an absolute journey. Moving to a strange town for so long has been a challenge. I never expected to be here this long, but I am glad you have got me through and made this another home for me.

Thank you to Dr. Zhongguo John Ma for giving me a chance when no one else would. I remember reaching out to you as a sophomore with no relevant experience, only my curiosity and passion. You've helped me to be more of a leader, and I thank you for that. Thank you to Dr. Debalina Ghosh for taking me under your wing. When it comes to working in the lab, you taught me everything I know, and I will never forget your kindness. Thank you to everyone else I researched with: Dr. Ammar Elhassan, Sazzadul Saykat, Syed Aqib, Saeed Davar, Levi Matthews, Evan Pindrock, Jaden Chin, Sam Steiger, and LaTasha Woodard. You all were so helpful to me.

Thank you to the entities that supported me in my research. I want to thank both the Tennessee Department of Transportation and the Alaska Department of Transportation & Public Facilities for their generous donations. I would also like to thank the Department of Civil & Environmental Engineering here at The University of Tennessee, Knoxville for supporting me and giving me a space to grow. I have been fortunate to be a part of this exemplary group.

Thank you to the professors, advisors, office workers, and custodians who would check on me to make sure I was alright. I appreciated having you all as shoulders to lean on.

Thank you to my friends for putting up with me on days when I was too stressed or too busy to see you all. Thank you for showing interest in my work; I know concrete isn't the most exciting material to most people. Thank you for listening as I talked out my problems. I will be there for you as long as I breathe.

And thank you to my family! Mom, Dad, Ethan, Gabrielle, Grandma, I love you all so much. I feel like we're getting closer as we get older. I apologize for all the times I didn't call or reach out because I was too tired. You all mean so much to me.

Abstract

Ultra-High Performance Concrete (UHPC) is an important material for modern structures, due to its high strength properties in regards to tension, compression and ductility. UHPC is well known to distinctly surpass common-use concrete in strength, but its relation to this concrete in durability is less documented. The intent of this thesis was to develop a UHPC mixture sufficient for different climates, and compare its durability properties to a normal-strength concrete mixture. Strength and durability related to weathering and surface resistance were considered, as well as material properties, to effectively withstand plausible environmental conditions. These parameters were then compared to the values of normal-strength concrete. The experimental results show that while UHPC possesses acceptable durability in most categories, it lacks exceptionable durability when simply meeting the design regulations. The findings can be used to further define UHPC, and improve the standards relating to it.

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Glossary

Air entrainer – a chemical admixture that facilitates the creation of air bubbles in the concrete.

This aids in freeze-thaw resistance by leaving room for the water to expand as it freezes

Curing – the process of regulating the temperature and moisture of concrete, for the purpose of developing strength and preventing cracking during the hardening process

Durability – the ability of concrete to withstand weathering, chemicals, and abrasion without significant loss in engineering serviceability

Electrical resistivity – a material's ability to oppose an electric current, which can provide insight into the distribution of pores in concrete

Freeze-thaw – a weathering process in which a crack fills with water, then expands when the water turns into ice. Continuation of this processes will continue to erode the material and expand the crack

HRWR – High-Range Water Reducer. It is a superplasticizer that can increase the flowability of a concrete mixture by dispersing the particles

Slump – a measure of concrete's flow and workability

Spalling – the breaking of a concrete's surface due to natural conditions

UHPC – Ultra-High Performance Concrete. A type of concrete optimized for compressive and tensile strength

Workability – the ability of concrete to be set, mixed, and compacted

Chapter 1: Introduction

Ultra-High Performance Concrete (UHPC) was developed specifically to achieve much higher compressive strength than normal-strength concrete (Reda et al., 1999). It is a relatively newer type of concrete, being commercially available for less than 30 years to date (Du et al., 2021). UHPC is generally viewed as more durable than normal-strength concrete in every way, due to the low water content, density of the concrete, and air content (Reda et al., 1999). For this reason, UHPC is highly coveted all over the world for structural applications. Its performance holds vast potential in creating more resilient and longer-lasting concrete structures. However, there is limited literature to justify its perception as being much more durable than common-use concrete. While strength is important and can provide some level of indication on durability, durability encompasses more than peak strength.

For an acceptable UHPC mixture, the concrete must meet certain strength standards. The most notable factor denoting a concrete as ultra-high performance is its compressive strength. The compressive strength must exceed 17,000 psi to be considered UHPC, a stark contrast from normal concrete which can have values as low as 2,500 psi. This strength is required to be met at 28 days of regulated curing, with the requirement exceeding 21,000 psi under steam curing conditions. There must also be significant tensile strength and ductility present, which relies heavily on fibers incorporated throughout the mixture (Mohammad Hasan et al., 2022). A specimen following ASTM C1609 has certain requirements, such as the maximum flexural strength exceeding 2,000 psi, and exceeding 1,500 psi before the first crack. The water content shall not exceed a quarter of the total water and cement content, so that the concrete is packed tighter together to protect against permeation (Du et al., 2021). This leads to resistivity from chemicals and freeze-thaw damage, which is especially important in northern climates such as Alaska (Ortiz-Salcedo et al., 2022).

The interest to use local materials to produce UHPC is beginning to expand all over the world, including the state of Alaska. While Alaska is a part of the United States, its distance of over 2,500 miles from the rest of the states makes it more difficult to receive the necessary resources. Many of the known UHPC materials, such as metakaolin, calcium carbonate, glass powder, and

rice husk ash are not cultivated or produced in Alaska (Du et al., 2021). Importing these materials is costly and inefficient, creating the need for a special mixture design with materials available in the Alaskan region. This also alludes to the need for increased research and international regulation of Ultra-High Performance Concrete. A lack of material or durability requirements could lead to the success of UHPC in one location and failure in another.

The widespread assumption is that Ultra-High Performance Concrete is comprehensibly more durable than normal-strength concrete, concrete with compressive strength between 3-6 ksi. This belief stems from the dense nature of UHPC; the smaller component sizes and lower water content lead to a product with less voids, which in turn can lead to less penetration of liquids (Du et al., 2021). This density, however, does not necessarily eliminate the penetration of substances, nor remove the threat of freeze-thaw damage. The density also fails to address several aspects of durability, such as microcracking and fire-resistance. There exists literature on creating normal and high strength concrete more durable, but there is a gap in information on the durability of UHPC made specifically to meet its strength standards (Khoury, 2000).

The intention of this thesis was to investigate the durability of Ultra-High Performance Concrete in comparison to normal-strength concrete. The consensus is that UHPC is inherently more durable than normal-strength concrete. Despite this, there is not sufficient evidence to back this claim. There are several strength-related criterion UHPC must achieve, qualifying it as stronger than regular concrete. These regulations do not exist in regard to durability of UHPC. Durability in itself is also multifaceted; it is possible to be more durable in one area, yet less durable in another. For this study, normal-strength concrete was developed, with several variations in mix design, all acceptable by government standard. Proceeding this, UHPC was developed meeting the strength requirements it must abide by to assume a designation as UHPC. Both concretes were then subjected to several durability tests. Finally, the components and properties were investigated to provide an understanding of these durability phenomena.

Chapter 2: Conceptual Overview

Ultra-High Performance Concrete achieves high strength and durability due to its material makeup. This concrete has a minimal amount of water incorporated throughout the mixture. This reduction of water eliminates unnecessary voids in the concrete, for a more compacted resultant entity (Du et al., 2021). This reduction on its own, however, drastically reduces the overall workability and flowability of the mixture. This is why a superplasticizer is needed to be incorporated into the mixture. Superplasticizers, specifically high-range water reducers (HRWR), are chemicals that get adsorbed onto cement particles to promote dispersion. The cement particles repel from each other, resulting in a better flowing mixture (Lohaus & Ramge, 2008). This leads to superior workability to normal concrete, despite the lower water content (Du et al., 2021). UHPC also achieves higher strength than typical concrete due to the fineness of dry ingredients. Using gradated fine materials drastically reduces the voids in the concrete and creates a much more compact final product. The density of the concrete and stronger bonds between materials results in a stronger concrete. With such a high level of compaction, and a low void ratio, it becomes difficult for water or chemicals to insert into the composite, reducing erosion, weathering, freeze-thaw damage, and ion penetration (Ortiz-Salcedo et al., 2022). Durability is also improved by the addition of fibers in the mixture. Fibers, typically being made of steel, provide added resistance to cracking. Being made of a different material, fibers remain elastic when concrete would typically crack (Yusuf et al., 2023). This not only adds durability, but adds tensile strength as well to a material with poor tensile capacity in comparison to compressive strength.

Flow, fiber segregation, temperature, and air content are all parameters that are necessary to be monitored during UHPC development. Ultra-High Performance Concrete should be very flowable, even with the reduction in water content. This allows the concrete to be self-consolidating, which is important for compaction and reduction of voids (Park et al., 2022). This flow also aids in fiber segregation; the ease of movement allows the fibers to disperse more easily in the mixing process. The temperature of the wet concrete is worth monitoring, as temperature can provide insight on the rates of reactions and late strength development (Du et

al., 2021). Air content also is important for void and freeze-thaw considerations (Ortiz-Salcedo et al., 2022).

Electrical resistivity, another durability parameter, measures a material's ability to resist electric current. In concrete, its purpose is to provide precise data regarding the specimen's permeability. This provides information about the concrete's ability to resist penetration. Lack of penetration resistance can lead to severe damage from natural occurrences, such as weathering and freeze-thaw (Ortiz-Salcedo et al., 2022). The electrical resistivity of the concrete is measured by using a Wenner probe, or probing instrument operating under a similar principle. A current is applied by the outer probes, and the inner probes measure the ions flowing through the liquid in the pores. For this reason, it is recommended to test the specimens while wet. The probes use the ions to measure the resistance ($K\Omega$) with respect to probe spacing (cm.) (Resipod, 2024). While initial measured value (apparent surface resistivity) is important for data interpretation, it is also important to correct this data in regard to cylindrical specimen geometry. This is because surface resistivity is a function of probe spacing and specimen size, which becomes less reliable for smaller specimens. This correction is especially important for estimating service life, as this conservative value is used when evaluating durability in regards to extended duration (AASHTO T 358, 2022).

Freeze-thaw resistance is a necessary consideration for defining concrete durability. Freeze-thaw resistance measures concrete's ability to maintain strength after cycles of freezing and thawing. This reduction in strength is due to the internal cracking that occurs from water in the concrete's pores (Ortiz-Salcedo et al., 2022). As the water continually expands and contracts from its temperature formation changes, the concrete sustains internal stresses (Hamada et al., 2022). There are several ways to test freeze-thaw performance, such as freeze-thaw chambers and measuring air content. The Super Air Meter (SAM) test is a newer method that arguably provides the most benefits. The Super Air Meter saves more time and materials than freeze-chambers, while providing more information than simply air content. SAM numbers are widely considered accurate in regards to predicting freeze-thaw performance (Hall et al., 2020).

Concrete is inherently more resistant to high temperatures than other building materials, such as steel and timber. Despite this, concrete still sees large reductions in strength when heat-damaged. Normal-strength concrete can lose over half of its strength after being exposed to red flame temperatures (600°C). High temperature resistance is also an important durability consideration, even though extreme fire events do not affect all concrete structures (Khoury, 2000).

Scanning Electron Microscopy (SEM) is a technique used to analyze specimens at high resolutions. SEM is especially important for analysis of patterns and formations smaller than human eyesight can detect. A scanning electron microscope instrument casts electrons onto a specimen, then captures them to produce an image, which can display at tens of thousands of times magnification. This can be helpful when assessing concrete durability, as pore structure, microcracks, and grain distribution can be investigated with this information from the enhanced visuals (Diamond & Huang, 2001).

Chapter 3: Development of Two Concrete Mixtures

To investigate the comparison between normal-strength concrete and UHPC, both types of concrete needed to be developed. First, normal-strength concrete abiding by government design was developed. Preceding the creation of this concrete, more concrete was designed to meet the minimum regulations to qualify as UHPC. This section details this process.

3.1: Control Concrete Mixtures

A detailed investigation into the fresh and hardened properties of optimized Class A concrete mixes was performed for the Tennessee Department of Transportation (TDOT). The study primarily examined the fresh and hardened properties of mixes to further understand the performance characteristics of Class A concrete. This is a typical concrete, displaying strength between 3-6 ksi. Made using limestone as the coarse aggregate, the main experimented variations were the use of manufactured sand opposed to natural sand, and reductions of cement from the reference mixture proportions.

Typical Tennessee Class A concrete was developed as a comparison, comprised of cement, coarse aggregate, intermediate aggregate, fine aggregate, fly ash, air entrainer, and normal-range water reducers. The cement used was Type 1L cement, also referred to as Portland Limestone Cement, as this cement has seen increased usage in recent years (Howard et al., 2015).

Intermediate aggregate was used to mitigate the vastness of size difference between the sand and the coarse aggregate. The fly ash chosen is classified as Class F and abides by ASTM C618. This concrete's materials were all from Tennessee and the directly neighboring regions.

These mixtures differ from UHPC standards due to the higher water/cement ratio, the incorporation of non-fine aggregates, the lower-ranged water reducers, the use air entrainer, and the reduced reliance on admixtures. **Table 3-1** displays the volumetric proportions of the Tennessee mixtures. The mixes were all labeled by class of concrete – type of limestone – type of sand – percent reduction of cement. For example, A-LS1-MS-0 denotes a Class A concrete,

Table 3-1: Tennessee Class A Concrete Mixture Proportions (Volume per 27ft³)

Mix ID	WR	AE	Cement	Fly Ash	CA	IA	Sand	Water
A-LS1-MS-0	0.01	1.62	2.15	0.89	6.55	4.25	7.45	4.07
A-LS1-MS-10	0.01	1.62	1.94	0.80	6.80	4.43	7.74	3.66
A-LS1-MS-20	0.01	1.62	1.72	0.71	7.09	4.57	8.02	3.26
A-LS2-NS-0	0.01	1.62	2.15	0.89	6.19	4.08	7.98	4.07
A-LS2-NS-10	0.01	1.62	1.94	0.80	6.37	4.31	8.29	3.66
A-LS2-NS-20	0.01	1.62	1.72	0.71	6.64	4.44	8.60	3.26
A-LS2-MS-10	0.01	1.62	1.94	0.80	6.39	5.59	6.98	3.66
A-LS3-MS-20	0.01	1.62	1.72	0.71	6.50	5.69	7.49	3.26

using limestone from location 1, manufactured sand, and 0% reduction of cement. The reduction of cement is in reference to its own weight.

The reduction of cement was accompanied by a reduction of fly ash to maintain a 3:1 cement and fly ash ratio. All aggregate concentrations (coarse aggregate, intermediate aggregate, and sand) were increased to maintain the same volume of 27 cubic ft and mitigate strength loss. The water concentration was also increased to maintain intended slump action. Water reducer was added as deemed necessary for workability during the mixing process. Due to the increase in water, despite the maintaining of a 0.45 water ratio, all mixes saw a decrease in water reducer needed. Air entrainer was also added to all of the mixes based on visual appearance of air bubbles in the mixture. A-LS1-MS-10 also had an addition of air entrainer, but less than 0.01% of the total weight (0.004%).

The curing of the Class A concrete and the UHPC was conducted at 23°C. The curing was performed in a lime water bath condition, which is an acceptable curing condition for Ultra-High Performance Concrete. Steam curing is usually seen as more optimal, leading to higher ultimate strength, but the utilized testing facility did not have steam curing capabilities. UHPC is required to cure at a minimum of 20°C, but sees an early strength increase all the way up to 90°C. A study shows this linear relationship in the equation:

$$\frac{f_{c7}}{f_{c7,T=90^{\circ}C}} = 0.0065T + 0.4246$$

Equation 3-1

where f_{c7} is the predicted compressive strength at 7 days, f_{c7} is the compressive strength at 7 days of 90°C curing, and T is the curing temperature in degrees Celsius from 20°C to 90°C in water bath curing (Park et al., 2022). Despite this ratio, these temperatures were not suitable for the Class A concrete, as the higher temperatures would have an adverse effect on the early strength.

3.2: Local UHPC Mix Design

A detailed investigation into the fresh and hardened properties of newly developed UHPC was performed for the Alaska Department of Transportation & Public Facilities (Alaska DOT&PF). The study primarily examined the fresh and hardened properties of mixes to acknowledge the

durability characteristics of UHPC. With a focus on using Type-1 Cement, the concrete was tested for its potential strength and resistance, to be later compared with typical concrete's abilities.

The UHPC developed in this study was comprised of cement, fine aggregate, fly ash, silica fume, high-range water reducer, and steel fibers, with water also incorporated into the mixture. Type 1 Portland cement from Alaska Basic Industries (ABI) was the main cement used due to its ease of access in the Alaskan region. White Portland cement from Federal White Cement Inc. was also used to provide a comparison for the primary mixture, as the Federal Highway Administration (FHWA) uses this cement in its ideal UHPC mixture. Both cements abide by ASTM C150. The fine aggregate used was Mason Sand/ Multipurpose Sand from Anchorage Sand and Gravel, a subsidiary of ABI. The average gradation of the sand, according to ABI, was provided in **Table 3-2**. Its absorption ratio and particle size distribution was also measured in the lab according to ASTM C128 and the Mastersizer 3000 respectively. The fly ash chosen is classified as Class F and abides by ASTM C618. The silica fume was provided by Master Builders Solutions and is classified as MasterLife SF 100. The HRWR used was MasterGlenium 7920. The steel fibers used for the composite had a 0.2 mm (0.008 in) diameter, with a 13 mm (0.5 in) length and aspect ratio of 65. The fibers were provided by Sumiden Wire and were compliant with ASTM A820.

The mixing of the UHPC followed the procedure of the FHWA when deemed applicable. The sand and silica fume were mixed together for five minutes, followed by the addition of cement and fly ash for another five minutes of mixing, followed by the addition of water then HRWR for another ten minutes of mixing, proceeded by the addition of steel fibers for another five minutes of mixing (FHWA 2024). This procedure succeeded with the tabletop mixer, however, this procedure was not applicable with a large drum mixer. The blade of a drum mixer does not disperse the particles as efficiently as with a propeller mixer. The utilized drum mixer also lacked an adjustable rotation speed, which limited its maximum capacity in revolutions per minute (rpm). The size also was a factor, as UHPC has less mixing success for larger quantities due to its density and enhanced difficulty to properly disperse the particles in relation to the mixer's capabilities (Du et al., 2021). To overcome this, the times on each of the steps were

Table 3-2: ABI Gradation Chart

Product ID #	Description	#4	#8	#16	#30	#50	#100	#200	F.M.
132020	Mason Sand	100	99	92	71	30	9.5	2.40	1.98

doubled, and scraping of the circumference of the drum was performed before each material addition, as well as in the middle of the water and HRWR mixing procedure. This procedural modification would have differed if the drum mixer had an increased rotational speed.

The chosen materials were experimented with to create pastes that could flow properly with the reduced amount of water. After the pastes were deemed adequate, sand was added to create concrete matrices. In the creation of matrices, the mixes were judged on compressive strength. The 28-day average compressive strength did not need to reach the final compressive strength requirement (17 ksi), but 90% was appropriate considering the gradation, curing, and fibers. For the final stage, steel fibers were added to the mixture to create concrete composites. The sand was properly gradated as well, to take into consideration the durability requirements and compressive strength requirement. The curing method was also changed from air curing to water bath curing, as water bath curing is recommended for UHPC (Hamada et al., 2022).

Following ASTM C128, the absorption ratio of the fine aggregate was found to be 0.4%. This was calculated from the absorption equation:

$$Absorption \% = 100\left[\frac{S - A}{A}\right]$$

Equation 3-2

where S is the mass of the saturated surface-dry specimen, and A is the mass of the oven-dry specimen. Using this information, as well as the densities of the materials, mixing of the pastes ensued. After paste optimization to find the general ingredient ratios for an acceptable slump, matrixes with sand were made with several different ratios to achieve compressive strengths. The mixture proportions by weight are presented in **Table 3-3**. Mixtures starting with A used Alaskan Portland Cement (Type 1) and mixtures with W used White Cement. The letter “m” labels the mixture as a matrix, as opposed to “c” which labels the mixture as a composite. The number following simply denotes the iteration of mixture.

Once this matrix was chosen, the mixture was adjusted. The original sand gradation is shown in **Figure 3-1**, including calculated D60, D30 and D10 values. These values are also displayed in **Table 3-4**, as well as the uniformity coefficient (Cu), Coefficient of Curvature (Cc), and fineness modulus (FM) values. These values all qualify as adequate values of sand fineness. Despite this, instead of using the initially graded mason sand, the sand was sieved further to retrieve three

Table 3-3: Matrix Mixture Proportions (Volume per 27ft³)

Mixture	Cement	Water	Sand	Fly Ash	Silica Fume	HRWR
Am1	8.64	5.01	5.53	3.96	3.38	0.49
Wm1	10.78	4.42	4.88	3.50	2.99	0.43
Am2	8.28	4.80	5.30	3.80	4.48	0.33
Wm2	10.39	4.26	4.71	3.38	3.96	0.29
Am3	8.67	3.77	5.55	3.97	4.69	0.35
Wm3	10.74	4.09	4.86	2.93	4.10	0.29
Am4	10.36	2.93	5.62	3.21	4.29	0.60
Wm4	11.42	2.74	5.26	3.00	4.02	0.56
Am5	9.14	4.88	4.75	3.53	4.29	0.41
Wm5	11.31	4.29	4.16	3.09	3.75	0.39
Am6	9.16	5.71	4.25	3.30	4.13	0.44
Wm6	11.35	5.01	3.73	2.90	3.63	0.39

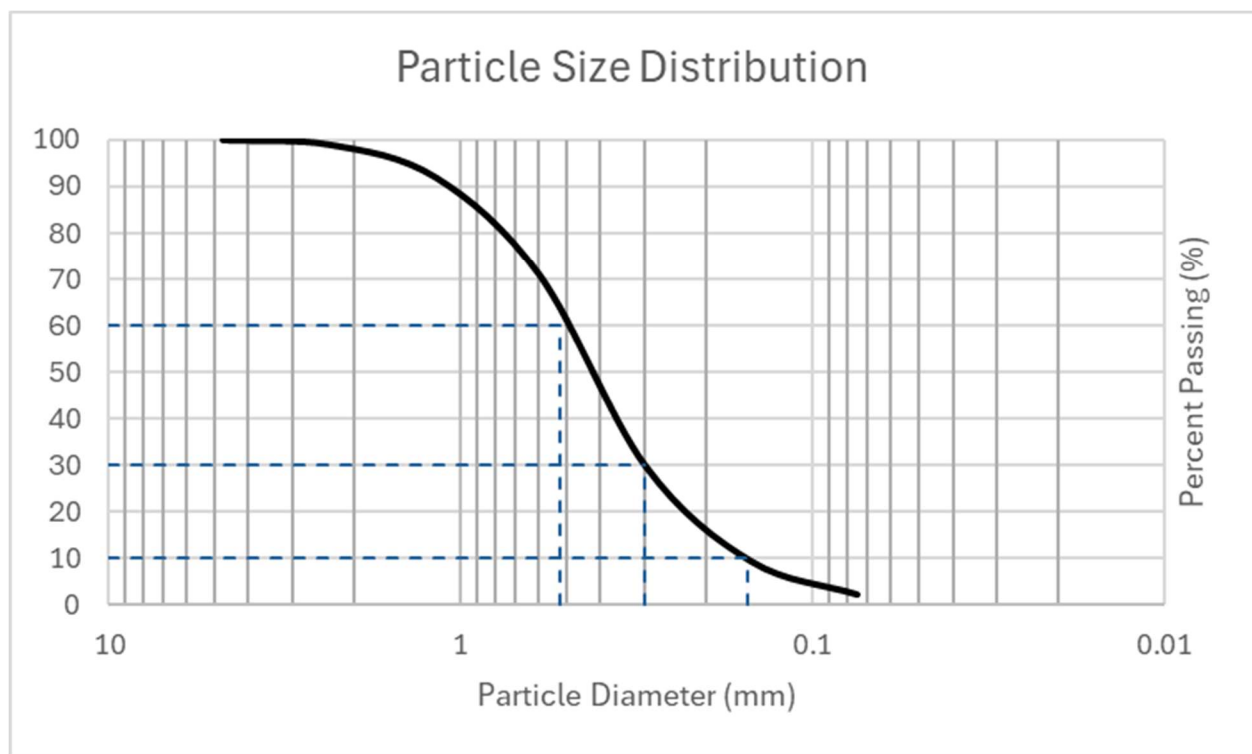


Figure 3-1: Sand Particle Size Distribution



Figure 3-2: Failed Matrix Specimen Interior

Table 3-4: Sand Particle Size Variable Data

Variable	D60 (mm)	D30 (mm)	D10 (mm)	Cu	Cc	FM
Value	0.52	0.30	0.15	3.38	1.13	1.99

different groups of sand. A third of the fine aggregate used passed through sieve No. 8, another third passed through sieve No. 18, and a third passed through sieve No. 35. This was done because despite the adequate sieving quality, the matrix specimens had distinct, larger aggregate particles visible. An example of this is shown in **Figure 3-2**. This internal irregularity could result in premature strength failures. Requiring all aggregates to pass through sieve No. 8 created a denser makeup without large particles to reduce the internal packing (Mohammad Hasan et al., 2022). This follows the continuous model theory, which offers that while small particle size is important for particle packing, using varying particle sizes further decreases the porosity and permeability (Du et al., 2021). This is supported by the Modified Andreasen & Andersen continuous model equation:

$$P(D) = \frac{D^q - D_{min}^q}{D_{max}^q - D_{min}^q} \times 100\%$$

Equation 3-3

where $P(D)$ is the target particle size distribution, D is the particle size of the material of interest, D_{min} is the minimum particle size of all materials, D_{max} is the maximum particle size of all materials, and q is the distribution modulus. This equation conveys that utilizing a minimum of three levels of gradation even of the same material improves the particle packing, with a target particle size distribution less than 100% being optimal (Du et al., 2021).

Steel fibers were also incorporated to transition the matrix to the final composite phase. Using 2% of steel fibers in a UHPC composite provides the greatest compressive strength, without the concerns of fiber agglomeration, so that was replicated in this testing (Yusuf et al., 2023). This percentage is also the minimum used to be considered a “high volume of fibers”, a trait that UHPC typically relies on for notable flexural performance (Du et al., 2021). The final proportions of the composite by weight are displayed in **Table 3-5** as well as in **Figure 3-3**.

Table 3-5: Composite Mixture Proportions (Volume per 27ft³)

Mixture	Cement	Water	Sand	Fly Ash	Silica Fume	HRWR	Steel Fibers
Ac5	10.32	3.80	6.71	3.10	2.69	0.29	0.10

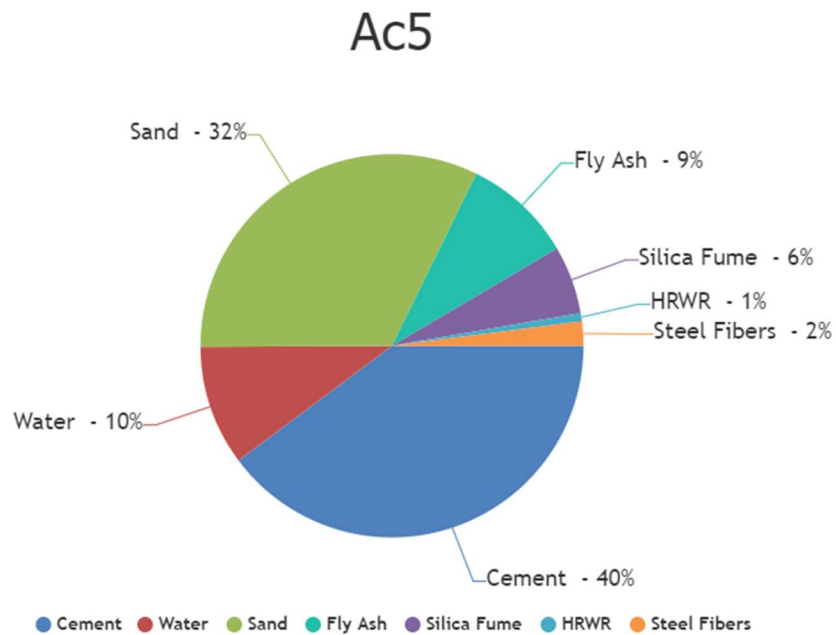


Figure 3-3: Composite Mixture Proportions by Weight

Chapter 4: Testing

4.1: Control Concrete Mixture

A series of assessments were conducted on various mixes to examine fresh properties including slump, unit weight, air content, and SAM number. Additionally, compressive strength testing at the 7-day mark was carried out to gauge early strength development, followed by the standard 28-day compressive strength test for its 99% predicted strength value. Prepared using a drum mixer, the experimental procedures were conducted in accordance with ASTM codes for the optimized mixes. The temperature was also monitored to note any environmental or internal irregularities.

4.1.1: Fresh Property Tests

The mixes subjected to batch testing for this project consistently exhibited an air content within the range of 6.0 ± 2.0 percent, aligning with the specifications mandated by the Tennessee Department of Transportation (TDOT). This adherence was crucial for mitigating potential fluctuations in test results arising from significant variations in air content. The air content values are displayed in **Table 4-1**. Mix A-LS1-MS-0 was the only outlier, with a batch-highest air content of 10.5%, while A-LS2-NS-10 had the lowest air content, valuing at 5.2%.

The SAM numbers of the mixes were also found during fresh property testing. These values are displayed in **Table 4-2**. This provides insight to the air void spacing factor, which is crucial for freeze-thaw durability. SAM numbers are ideally less than 0.2 for excellent performance against freeze-thaw (Hall et al., 2020). However, as a general consensus, 0.3 as an upper limit is seen as acceptable in most cases (Tanesi et al., 2016). The errors in the table means the Super Air Meter could not adequately detect the voids in the mix.

Table 4-3 presents the slump variations observed across optimized mixes employing various aggregates for initial batches. A slump between 2-4 inches was expected for these mixtures. Adjustment of water-reducing admixtures (WRA) facilitated achieving the desired slump consistency. Notably, mixtures with a slump below 3 inches were considered acceptable only if proper consolidation into specimen molds could be achieved.

Table 4-1: Air Content Percentage of TDOT Mixtures

Mix ID	Air Content(%)
A-LS1-MS-0	10.5
A-LS1-MS-10	6.6
A-LS1-MS-20	5.9
A-LS2-NS-0	6.3
A-LS2-NS-10	5.2
A-LS2-NS-20	7.2
A-LS2-MS-10	7.8
A-LS3-MS- 20	5.4

Table 4-2: SAM Number of TDOT Mixtures

Mix ID	SAM Number
A-LS1-MS-0	0.17
A-LS1-MS-10	Error
A-LS1-MS-20	Error
A-LS2-NS-0	0.26
A-LS2-NS-10	0.28
A-LS2-NS-20	0.36
A-LS2-MS-10	0.19
A-LS3-MS- 20	0.14

Table 4-3: Slump of TDOT Mixtures

Mix ID	Slump (in)
A-LS1-MS-0	3.75
A-LS1-MS-10	5.00
A-LS1-MS-20	4.00
A-LS2-NS-0	3.50
A-LS2-NS-10	2.50
A-LS2-NS-20	4.50
A-LS2-MS-10	3.00
A-LS3-MS- 20	3.00

4.1.2: Compressive Strength

As per TDOT specifications, Class A concrete is mandated to possess a minimum compressive strength of 3000 psi at the end of 28 days. To assess the early-age strength development, compressive strength testing was conducted on three cylindrical specimens from each mix at the 7-day mark. **Figure 4-1** shows a compression test conducted in the lab. **Table 4-4** and **Figure 4-2** display the compressive strength of the mixtures at 7 and 28 days. A-LS2-MS-10 and A-LS3-MS-20 were not tested for compressive strength. The reduction of cement showed a strong correlation with the reduction of compressive strength in the manufactured sand specimens. This correlation was not as strong in the natural sand specimens, as the samples with 20% cement reduction had an equal average compressive strength as the samples with 10% cement reduction at 7 days of curing, and a greater average compressive strength at 28 days.

4.1.3: Surface Resistivity

Surface resistivity was measured for the TDOT specimens. As the surface resistivity increases, the chloride ion penetration decreases. In **Table 4-5**, the values below 12 K Ω -cm are considered high, the values between 12 and 21 K Ω -cm are considered moderate, and the values between 21 and 37 K Ω -cm are classified as low in terms of ion penetration. Values between 37 and 254 K Ω -cm are classified as very low (AASHTO T 358, 2022). All tested specimens had typical concrete resistivity values at 28 days, which is moderate or slightly high. All tested specimens had low penetration at 56 days. As the concrete has more time to cure, it continues to harden and achieve greater strength and durability (Park et al., 2022). Fly ash presence is a significant contributor to surface resistivity. Fly ash does consist of chloride ions, but its significance is attributed to its ability to decrease the porosity of a mixture. With its fineness, it is able to fill pores and reduce the ability of substances to penetrate the hardened composite (Ortiz-Salcedo et al., 2022).

Specimen A-LS1-MS-0 had the highest apparent resistivity (lowest ion penetration). **Figure 4-3** shows the testing process for surface resistivity being conducted on a single specimen, while **Figure 4-4** displays multiple specimen in the holder. The testing followed the procedure in AASHTO T 358, with three concrete cylinders of 8-inch height and 4-inch diameter. The coefficient of variation was considered for the samples, as a variation value over 7.5% required repetition of the test. The coefficient of variation was calculated following the equation:



Figure 4-1: Compression Test Class A Cylinder

Table 4-4: Compressive Strength of TDOT Mixtures

Mix ID	Compressive Strength (ksi) (7 days)	Compressive Strength (ksi) (28 days)
A-LS1-MS-0	3.80	5.92
A-LS1-MS-10	3.25	4.54
A-LS1-MS-20	1.78	3.12
A-LS2-NS-0	3.19	4.81
A-LS2-NS-10	2.42	4.34
A-LS2-NS-20	2.42	4.68

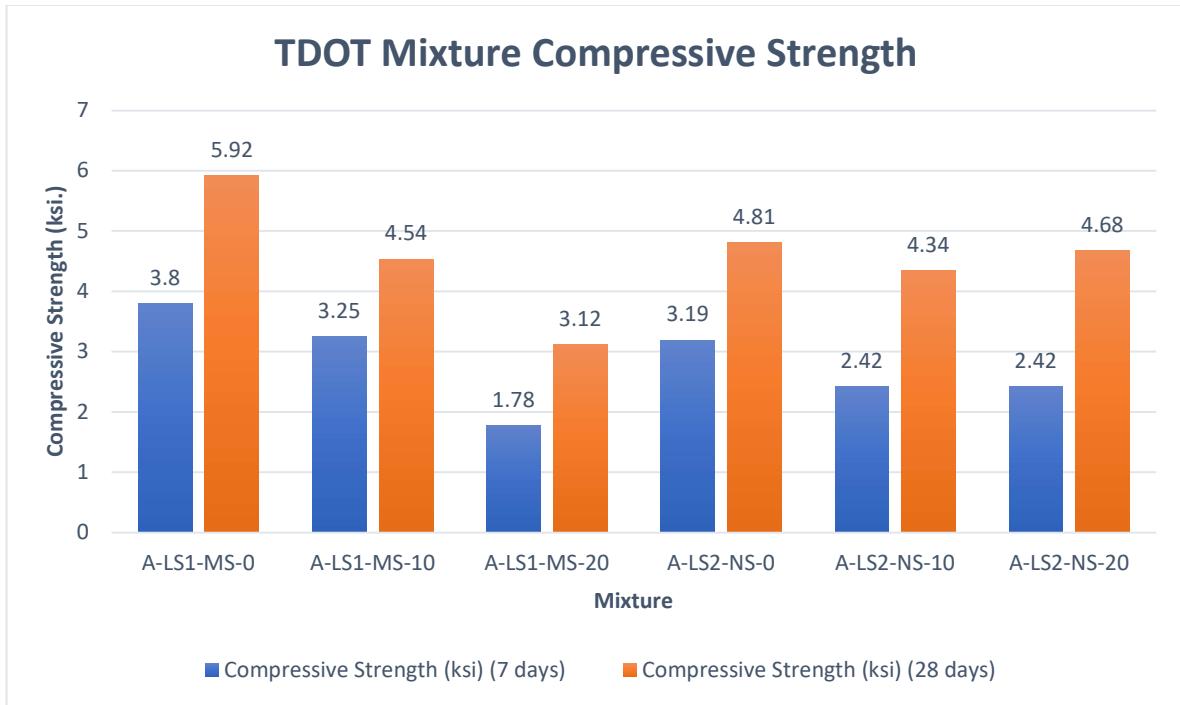


Figure 4-2: Compressive Strength of TDOT Mixtures

Table 4-5: Average Apparent Surface Resistivity of TDOT Mixtures

Mix ID	28 Day Resistivity (K Ω -cm)	56 Day Resistivity (K Ω -cm)
A-LS1-MS-0	14.43	26.09
A-LS1-MS-10	18.49	36.81
A-LS1-MS-20	12.23	22.11
A-LS2-NS-0	14.28	27.18
A-LS2-NS-10	11.90	31.99
A-LS2-NS-20	19.30	37.86
A-LS2-MS-10	16.21	35.68
A-LS3-MS-20	14.83	29.07



Figure 4-3: Surface Resistivity Testing In-Action



Figure 4-4: Surface Resistivity Samples in Holder

$$CV = \frac{SD}{AVG} * 100\%$$

Equation 4-1

Where CV is the coefficient of variation, SD is the standard deviation, and AVG is the average of the values.

Despite their variations, all of these mixtures are Class A concrete. No significant trends can be seen from one group compared to the other in regards to surface resistivity. **Figure 4-5** shows the average resistivity values of the mixtures, while **Figure 4-6** and **Figure 4-7** show the individual values of the surface resistivity and service-life resistivity, respectively. Using manufactured sand did not show a strong deviation of results compared to natural sand at 28 days or 56 days. Natural sand has a more rounded shape than the unnatural, machine-made sand, which theoretically would lead to less bonding strength (Tan et al., 2022). However, even as the leading material in percent by weight, this did not seem to significantly alter the results. The reduction of cement also lacked any surmisable trend regarding surface resistivity. For example, 20% reduction led to the lowest resistivity value, and thus highest penetration, for the A-LS1-MS mixes, but the opposite was true of the A-LS2-NS mixes. A-LS2-NS-10 and A-LS3-MS-20 were observed to compare the effect of using limestones from different regions. They produced differing results than their LS1 counterparts, but the values remained high-to-moderate in penetration. This lack of surface resistivity deviation is due to the similar mixture proportions. Even though there was a 20% reduction in cement, not even a 3% change occurred in any of the materials in total mix percent by weight, so these values being similar can be attributed to their similar composition. Even though the aggregates were from different locations, they had minimal impact. Surface resistivity is largely affected by pores and voids, and with the standardized air content, this similarity in values is logical.

High-to-moderate penetration was expected for these mixtures at 28-days. The use of coarse aggregate makes it difficult to eliminate voids in the concrete. Even with the supplementation of intermediate aggregate, using large particles can be expected to lead to large permeation (Mohammad Hasan et al., 2022). This corresponds to the 28-day testing results of these mixtures, as all have average values in the high-to-moderate tier. This trend is especially true due to the

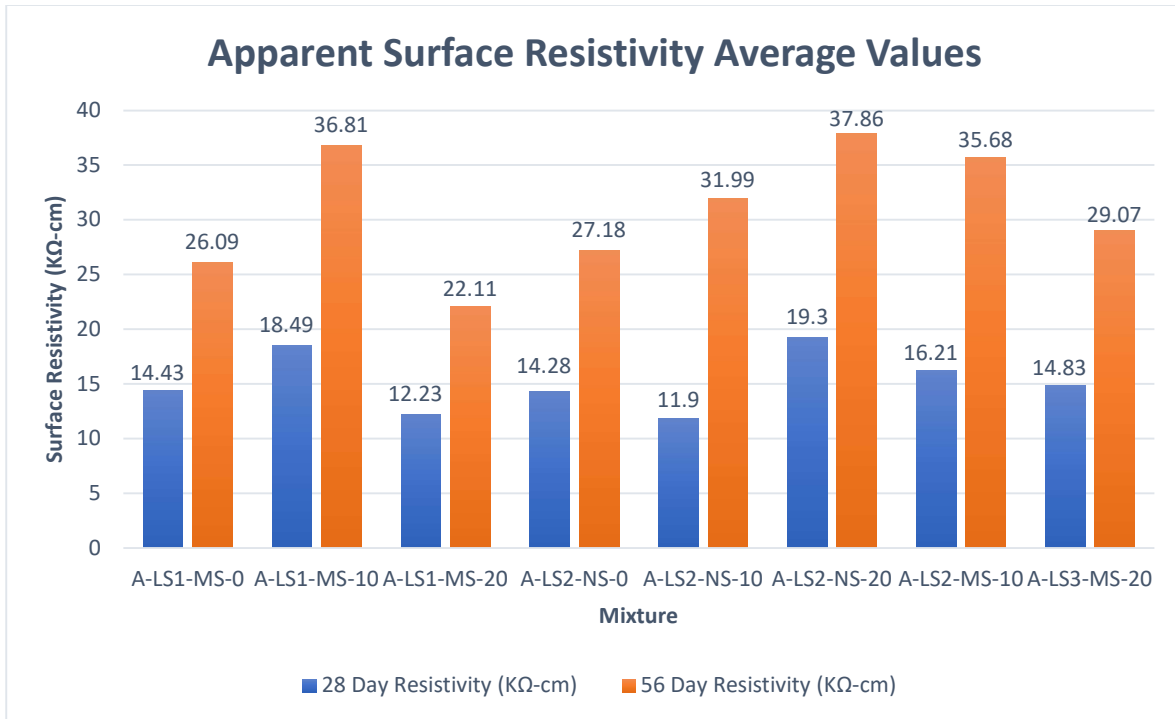


Figure 4-5: Average Apparent Surface Resistivity of TDOT Mixtures

Mix ID	Elapsed Days	Sample No	Apparent Surface Resistivity (KQ-cm)							
			0	90	180	270	0	90	180	270 Average
A-LS1-MS-0	28	1	13.75	14.52	14.41	14.30	13.42	14.63	14.63	14.52
		2	15.40	13.86	14.30	14.30	15.62	14.19	14.30	14.74
	56	1	24.97	26.40	25.74	26.40	25.74	25.63	26.18	25.41
		2	26.84	25.74	25.85	27.39	25.96	25.63	26.07	27.50
A-LS1-MS-10	28	1	20.79	19.58	19.58	19.36	20.90	19.14	19.91	19.36
		2	16.61	18.92	17.60	16.83	16.72	18.81	17.05	16.94
		3	16.94	17.60	19.14	19.03	17.16	18.15	18.92	18.70
	56	1	37.84	37.07	37.51	38.28	37.40	37.18	37.62	37.84
		2	36.52	35.31	35.20	34.98	35.97	34.54	34.54	35.31
		3	38.39	36.52	37.18	37.84	38.28	37.18	37.18	37.84
A-LS1-MS-20	28	1	13.53	11.66	11.99	12.32	12.98	11.99	12.65	12.10
		2	12.43	12.10	11.77	12.65	12.10	11.88	12.32	12.65
		3	11.99	11.66	12.43	12.76	11.66	11.77	12.21	11.99
	56	1	21.89	21.45	21.45	22.88	21.45	21.01	20.68	22.11
		2	20.46	22.66	21.12	22.88	19.91	21.56	22.22	22.00
		3	20.90	20.35	23.21	22.22	21.01	20.46	22.88	22.33
A-LS2-NS-0	28	1	14.08	14.30	15.18	14.96	14.08	13.20	14.41	13.97
		2	13.64	15.18	13.64	13.53	13.97	14.96	14.52	13.53
		3	13.53	14.41	14.85	14.41	14.63	14.19	15.07	14.41
	56	1	25.96	28.05	26.95	27.28	25.96	29.48	28.05	26.40
		2	28.05	25.08	27.17	27.94	26.84	25.63	27.61	27.28
		3	26.73	25.74	27.94	28.05	26.73	26.95	28.05	28.38
A-LS2-NS-10	28	1	12.43	11.99	11.33	11.66	12.21	11.66	11.66	11.55
		2	11.66	11.44	11.66	11.33	11.88	11.55	11.99	11.77
		3	12.21	12.76	12.43	11.66	12.32	12.21	12.65	11.66
	56	1	33.88	33.55	33.00	30.36	31.79	34.21	32.78	31.24
		2	31.68	30.47	31.24	31.02	31.24	30.47	32.34	30.25
		3	33.33	32.12	32.56	32.12	33.00	31.79	32.12	30.91
A-LS2-NS-20	28	1	19.80	21.56	20.90	19.69	20.24	19.14	20.68	19.36
		2	17.16	21.45	18.37	18.37	18.92	16.50	16.94	18.48
		3	17.82	21.78	19.03	18.81	19.69	20.79	18.04	19.69
	56	1	38.28	38.72	38.50	38.28	38.72	39.16	38.94	38.61
		2	37.51	35.42	35.86	36.08	36.74	34.98	35.53	35.53
		3	38.72	39.16	38.94	38.94	38.50	40.04	38.83	38.72
A-LS2-MS-10	28	1	17.93	16.61	16.39	17.49	17.71	17.49	16.61	17.71
		2	15.51	15.84	15.29	15.73	15.84	15.95	15.62	15.84
		3	15.84	15.51	16.50	15.07	15.73	15.18	16.61	15.07
	56	1	36.96	37.62	35.75	35.53	35.97	37.62	36.19	35.42
		2	36.19	35.31	35.53	34.10	34.98	35.53	36.85	34.65
		3	35.86	36.74	34.21	34.43	36.74	36.19	33.77	33.99
A-LS3-MS-20	28	1	14.52	15.95	14.41	14.96	15.29	15.73	14.63	14.63
		2	15.62	13.86	14.74	14.85	15.29	14.19	14.41	13.97
		3	15.18	13.86	14.63	15.29	15.18	14.85	14.52	15.29
	56	1	29.81	26.95	30.03	31.35	30.47	26.84	30.36	30.69
		2	28.60	28.71	28.27	28.16	28.71	28.82	27.17	28.60
		3	29.37	30.14	28.82	28.82	29.04	30.25	28.93	28.82

Figure 4-6: Apparent Surface Resistivity for Normal-Strength Concrete

Mix ID	Elapsed Days	Sample No	Surface Resistivity (KQ-cm)							
			0	90	180	270	0	90	180	270 Average
A-LS1-MS-0	28	1	7.16	7.56	7.51	7.45	6.99	7.62	7.62	7.56
		2	8.02	7.22	7.45	7.45	8.14	7.39	7.45	7.68
	56	1	13.01	13.75	13.41	13.75	13.41	13.35	13.64	13.23
		2	13.98	13.41	13.46	14.27	13.52	13.35	13.58	14.32
A-LS1-MS-10	28	1	10.83	10.20	10.20	10.08	10.89	9.97	10.37	10.08
		2	8.65	9.85	9.17	8.77	8.71	9.80	8.88	8.82
		3	8.82	9.17	9.97	9.91	8.94	9.45	9.85	9.74
	56	1	19.71	19.31	19.54	19.94	19.48	19.36	19.59	19.71
		2	19.02	18.39	18.33	18.22	18.73	17.99	17.99	18.39
		3	19.99	19.02	19.36	19.71	19.94	19.36	19.36	19.71
A-LS1-MS-20	28	1	7.05	6.07	6.24	6.42	6.76	6.24	6.59	6.30
		2	6.47	6.30	6.13	6.59	6.30	6.19	6.42	6.59
		3	6.24	6.07	6.47	6.65	6.07	6.13	6.36	6.24
	56	1	11.40	11.17	11.17	11.92	11.17	10.94	10.77	11.52
		2	10.66	11.80	11.00	11.92	10.37	11.23	11.57	11.46
		3	10.89	10.60	12.09	11.57	10.94	10.66	11.92	11.63
A-LS2-NS-0	28	1	7.33	7.45	7.91	7.79	7.33	6.88	7.51	7.28
		2	7.10	7.91	7.10	7.05	7.28	7.79	7.56	7.05
		3	7.05	7.51	7.73	7.51	7.62	7.39	7.85	7.51
	56	1	13.52	14.61	14.04	14.21	13.52	15.35	14.61	13.75
		2	14.61	13.06	14.15	14.55	13.98	13.35	14.38	14.21
		3	13.92	13.41	14.55	14.61	13.92	14.04	14.61	14.78
A-LS2-NS-10	28	1	6.47	6.24	5.90	6.07	6.36	6.07	6.07	6.02
		2	6.07	5.96	6.07	5.90	6.19	6.02	6.24	6.13
		3	6.36	6.65	6.47	6.07	6.42	6.36	6.59	6.07
	56	1	17.65	17.47	17.19	15.81	16.56	17.82	17.07	16.27
		2	16.50	15.87	16.27	16.16	16.27	15.87	16.84	15.76
		3	17.36	16.73	16.96	16.73	17.19	16.56	16.73	16.10
A-LS2-NS-20	28	1	10.31	11.23	10.89	10.26	10.54	9.97	10.77	10.08
		2	8.94	11.17	9.57	9.57	9.85	8.59	8.82	9.63
		3	9.28	11.34	9.91	9.80	10.26	10.83	9.40	10.26
	56	1	19.94	20.17	20.05	19.94	20.17	20.40	20.28	20.11
		2	19.54	18.45	18.68	18.79	19.14	18.22	18.51	18.51
		3	20.17	20.40	20.28	20.28	20.05	20.85	20.22	20.17
A-LS2-MS-10	28	1	9.34	8.65	8.54	9.11	9.22	9.11	8.65	9.22
		2	8.08	8.25	7.96	8.19	8.25	8.31	8.14	8.25
		3	8.25	8.08	8.59	7.85	8.19	7.91	8.65	7.85
	56	1	19.25	19.59	18.62	18.51	18.73	19.59	18.85	18.45
		2	18.85	18.39	18.51	17.76	18.22	18.51	19.19	18.05
		3	18.68	19.14	17.82	17.93	19.14	18.85	17.59	17.70
A-LS3-MS-20	28	1	7.56	8.31	7.51	7.79	7.96	8.19	7.62	7.62
		2	8.14	7.22	7.68	7.73	7.96	7.39	7.51	7.28
		3	7.91	7.22	7.62	7.96	7.91	7.73	7.56	7.96
	56	1	15.53	14.04	15.64	16.33	15.87	13.98	15.81	15.98
		2	14.90	14.95	14.72	14.67	14.95	15.01	14.15	14.90
		3	15.30	15.70	15.01	15.01	15.13	15.76	15.07	15.01

Figure 4-7: Corrected Surface Resistivity for Normal-Strength Concrete

intentional reduction of cement, as well as the lesser percentage of fly ash. The resistivity values corrected with respect to specimen geometry are displayed in

Much of the overall strength of the concrete matrices could be attributed to the level of cohesion of the mix. A mix with less than 5 psi could be predicted even before the sample was officially tested in compression. The samples with poor compaction were filled with spacious voids, causing the cubes to fail before their theoretical peak strength. These mixing complications were due to a lack of water compared to typical concrete, leading to less flowability and workability. Some matrix samples had larger failures due to the lack of sieved fine aggregate, which was corrected at the composite stage. Examples of these differences are shown in **Figure 4-18**, **Figure 4-19** and **Figure 4-20**.

4.2.2: Fresh Property Tests

The concrete composite was designed to be self-consolidating concrete. This ensures the UHPC water limitation does not prevent the concrete from being workable. The concrete's flow diameter exceeded 30 inches, the maximum diameter of the non-porous slump board used. This passes the minimum diameter requirement of 8 inches (Mohammad Hasan et al. 2022). This test is shown in **Figure 4-21**. While large flow values can sometimes indicate inopportune .

4.1.4: Section Summary

Normal-strength concrete was developed with slight mixture alterations to analyze the intrinsic performance with varying material proportions, while also providing multiple mixtures to be compared with UHPC. A-LS2-NS-0 is the most standardized of the Class A mixtures. With its lack of cement reduction and use of natural sand, it deviates the least from the Class A standard mixture. It exhibited moderate surface resistivity, sufficient air content, sufficient slump, and required compressive strength at 7 and 28 days. **Figure 4-8** shows the material proportions of A-LS2-NS-0 by weight.

4.2: Local UHPC Mix Design

The main attributes tested were compressive strength, air content, slump, surface resistivity. The compressive strength of the concrete matrices were measured according to ASTM C109. The

matrix and composite cubes were cast in stainless steel and bronze molds, both conforming to ASTM C109, displayed in **Figure 4-9** and **Figure 4-10**. The cubes were compressed using a Model 5593 SATEC Series Static Hydraulic System from Instron after programming it to output the desired results for a 2-inch cube. A matrix cube in the machine setup is displayed in **Figure 4-11**. The cubes were cast to maximize the available materials, but matrix cylinders were also cast to verify the accuracy of the cube compressive measurements. The concrete matrix cylinders were compressed according to ASTM C39. These 4-inch (diameter) by 8-inch (height) cylinders were tested using a Gilson 500,000lbf Concrete Compression Machine. The air content was determined using a Super Air Meter (SAM). The slump was measured according to ASTM C143. The surface resistivity was determined following AASHTO T 358.

4.2.1: Matrix Compressive Strength

The 7-day and 28-day compressive strengths of the mixtures are displayed in **Table 4-7** and **Figure 4-12**. There are values not displayed in the visuals because the mixtures that did not achieve half of the required compressive strength (8.5 ksi) were not tested again at 28 days. An example matrix breakage is displayed in **Figure 4-13**. According to ASTM C39, this is most

Table 4-6: Average Corrected Surface Resistivity of TDOT Mixtures

Mix ID	28 Day Resistivity (K Ω -cm)	56 Day Resistivity (K Ω -cm)
A-LS1-MS-0	7.52	13.59
A-LS1-MS-10	9.63	19.17
A-LS1-MS-20	6.37	11.52
A-LS2-NS-0	7.44	14.16
A-LS2-NS-10	6.20	16.66
A-LS2-NS-20	10.05	19.72
A-LS2-MS-10	8.44	18.58
A-LS3-MS-20	7.72	15.14

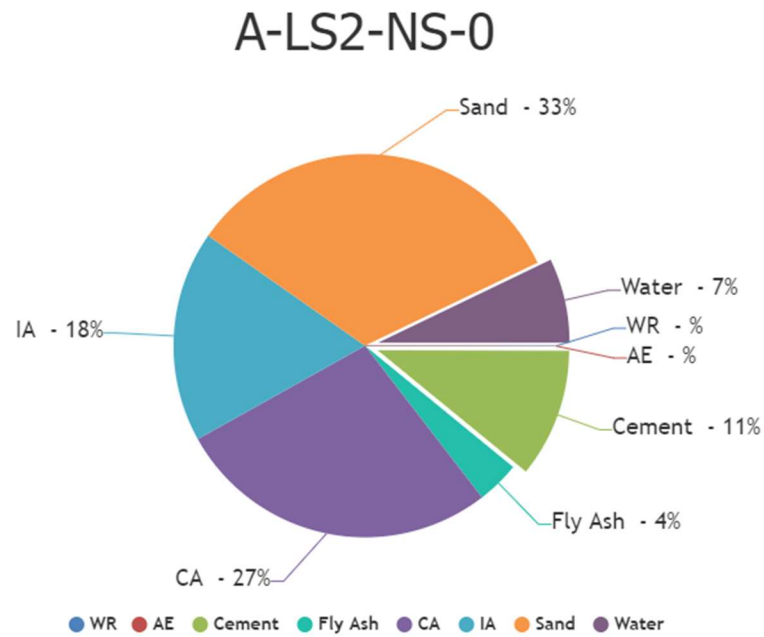


Figure 4-8: A-LS2-NS-0 Mixture Proportions (Percent by Weight)



Figure 4-9: Stainless Steel Concrete Mold



Figure 4-10: Bronze Concrete Cube Mold



Figure 4-11: Matrix Compression Setup

Table 4-7: Matrix Compressive Strengths

Mixture	7-Day Average (ksi)	28-Day Average (ksi)
Am1	8.75	13.50
Wm1	15.25	16.00
Am2	11.25	12.00
Wm2	2.75	-
Am3	10.00	11.75
Wm3	1.25	-
Am4	0.38	-
Wm4	0.33	-
Am5	14.00	15.00
Wm5	8.42	-
Am6	10.00	11.50
Wm6	12.00	13.25

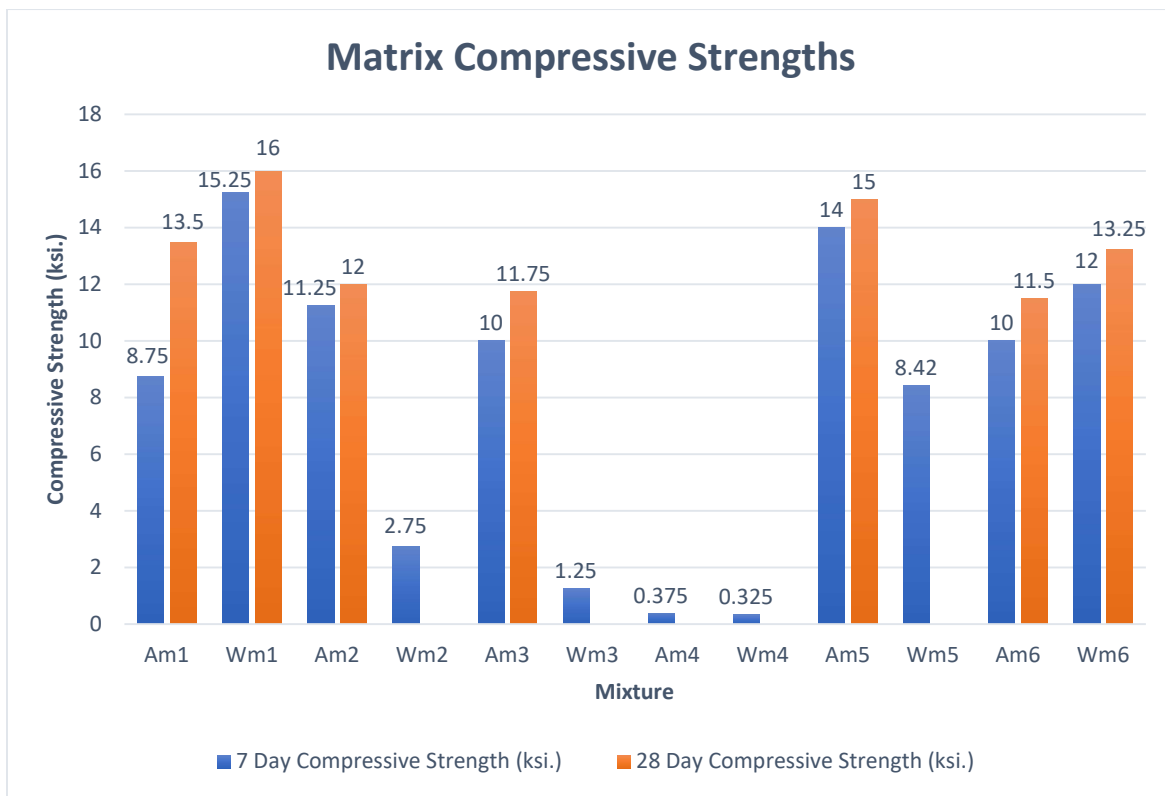


Figure 4-12: Matrix Compressive Strengths



Figure 4-13: Post-Compression Matrix Specimen

similar to a type 5 breakage, which is common in cylinders with rough surfaces or less than ideal cap bonding. A specimen compressed past failure is shown in **Figure 4-14**.

The matrix mixture chosen to proceed with for composite testing was Am5, as it had an average 15 ksi. compressive strength, which was the strongest for Portland Cement mixtures. With improved gradation, curing, and the addition of steel fibers, Am5 could most likely reach the 17 ksi. requirement. It also had the strongest individual cube, with a specimen reaching 16.5 ksi. The matrix specimen were also tested in cylindrical specimens to verify the replicability of the mixture performance, as well as the effect of specimen shape on the strength quality. Adverse reactions due to shape change could indicate poor bonding of the mixture. A matrix cylinder in the machine setup is displayed in **Figure 4-15**. The cylinders had an average compressive strength of 14.8 ksi., which reasonably correlates to the cubic mold average of 15 ksi. A cylinder directly after testing is displayed in **Figure 4-16**. The breakage pattern also was the same with the cylinders, which also verifies the consistency of the mixture and testing. The cracking of the cylindrical specimen can be seen in **Figure 4-17**.

Much of the overall strength of the concrete matrices could be attributed to the level of cohesion of the mix. A mix with less than 5 psi could be predicted even before the sample was officially tested in compression. The samples with poor compaction were filled with spacious voids, causing the cubes to fail before their theoretical peak strength. These mixing complications were due to a lack of water compared to typical concrete, leading to less flowability and workability. Some matrix samples had larger failures due to the lack of sieved fine aggregate, which was corrected at the composite stage. Examples of these differences are shown in **Figure 4-18**, **Figure 4-19** and **Figure 4-20**.

4.2.2: Fresh Property Tests

The concrete composite was designed to be self-consolidating concrete. This ensures the UHPC water limitation does not prevent the concrete from being workable. The concrete's flow diameter exceeded 30 inches, the maximum diameter of the non-porous slump board used. This passes the minimum diameter requirement of 8 inches (Mohammad Hasan et al. 2022). This test is shown in **Figure 4-21**. While large flow values can sometimes indicate inopportune



Figure 4-14: Failed Matrix Specimen in Instrument



Figure 4-15: Cylindrical Matrix Compression Setup



Figure 4-16: Cylindrical Post-Compression Matrix Specimen



Figure 4-17: Cylindrical Matrix Cracking Pattern



Figure 4-18: Well-Compacted Matrix Samples



Figure 4-19: Poorly-Compacted Matrix Samples



Figure 4-20: Cracked Matrix Specimen



Figure 4-21: Composite Post-Slump

segregation of aggregates or fibers, the mixture remained homogeneous (Du et al., 2021). Regarding other fresh property results, the composite mixture had an air content value of 0.5% and a SAM number of 0.27. These values are evident in **Figure 4-22** and **Figure 4-23**.

4.2.3: Composite Compressive Strength

The composites were made into cubes. This is typically done with larger, cylindrical specimens, but the fibers used were 0.5 inches long, which is less than the recommended 3:1 mold width to fiber length ratio. This means the specimen had adequate size for the fibers to disperse (Yusuf et al., 2023). **Figure 4-24** shows the cubes right after mixing.

Concrete with fibers is expected to reach about 90% of its strength 14 days after its mixed with proper curing (Kabir et al., 2012). The compressive strength at 14 days can also be used as a predictor of later compressive strength, as found in a study, which prompted the equation:

$$f'_{c,D} = \frac{D}{D + q} p$$

Equation 4-2

where $f'_{c,D}$ is the compressive strength of the concrete at day D, D is the days of curing, and p and q are constants. The constants, p and q, are determined from the equation:

$$p = -4.527 - 1.041q + 1.373f_{c,14} + 0.1406qf_{c,14} - 0.0125f_{c,14}^2$$

Equation 4-3

where $f_{c,14}$ is the compressive strength of the concrete at day 14 (Kabir et al., 2012). The constant q is determined with p in a system of equations. The samples tested at 14 days had an average compressive strength of 22.1 ksi, with a maximum specimen strength of 23 ksi. This thoroughly exceeds the 17 ksi requirement. **Figure 4-25** shows the 23 ksi specimen after completion of the test, while **Figure 4-26**, **Figure 4-27**, **Figure 4-28**, **Figure 4-29** show specimens of that test at various angles. **Figure 4-30** shows the force with respect to displacement during the procedure for one of the samples. It's important to understand that the displacement is in reference to the lower platform of the machine, not the specimen itself.

The concrete was tested again 28 days after the initial mixing process. This data could give rise to the time-related strength properties of the mix. The tested samples had an average

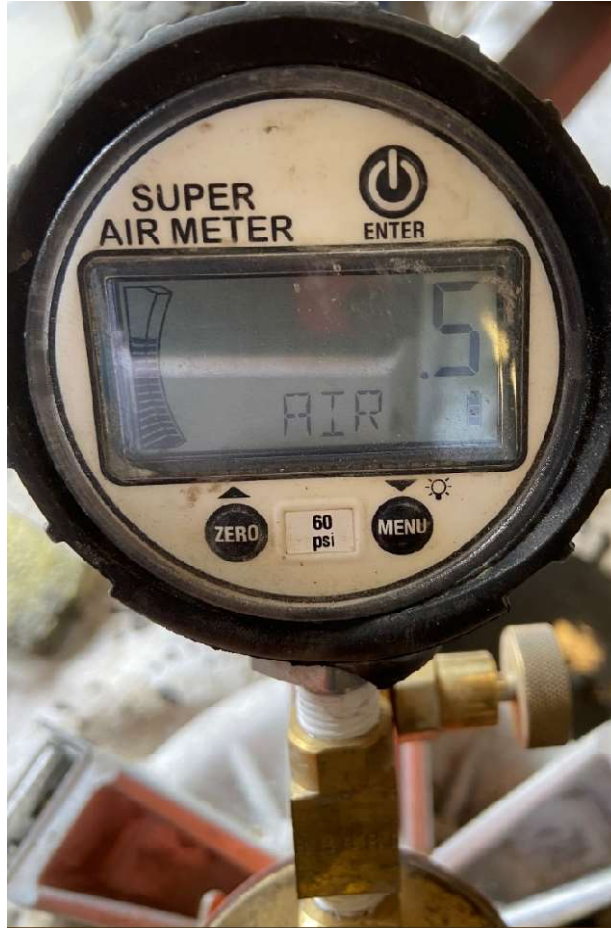


Figure 4-22: UHPC Air Content Reading

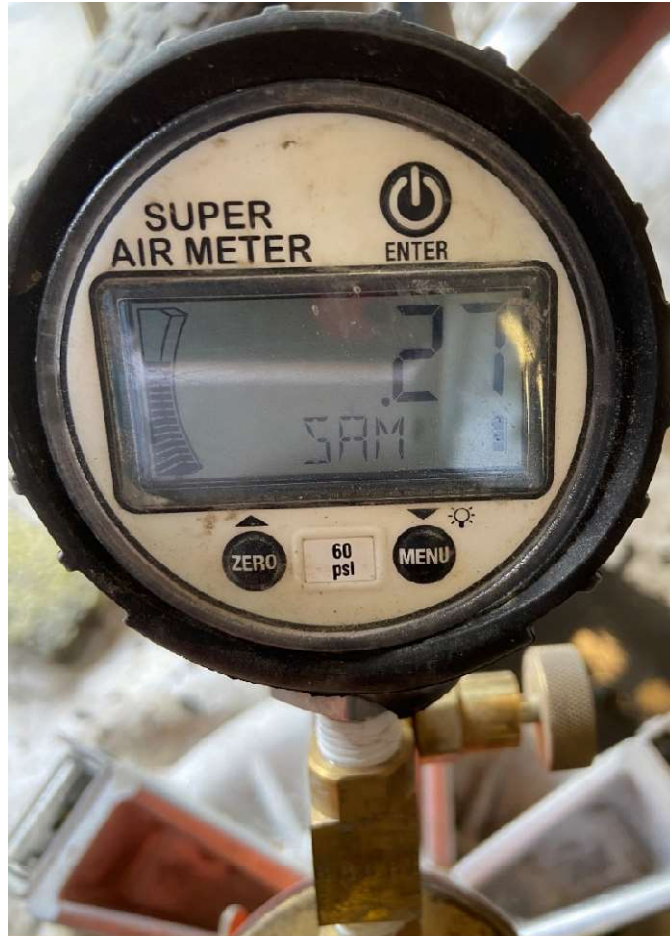


Figure 4-23: UHPC SAM Number Reading



Figure 4-24: Fresh Composite Cubes



Figure 4-25: Post-Compression Composite Cube



Figure 4-26: 14 Day Composite Specimen Post-Compression (Elevation View)



Figure 4-27: 14 Day Composite Specimen Post-Compression (Plan View)



Figure 4-28: 28 Day Composite Specimen Post-Compression (Elevation View)

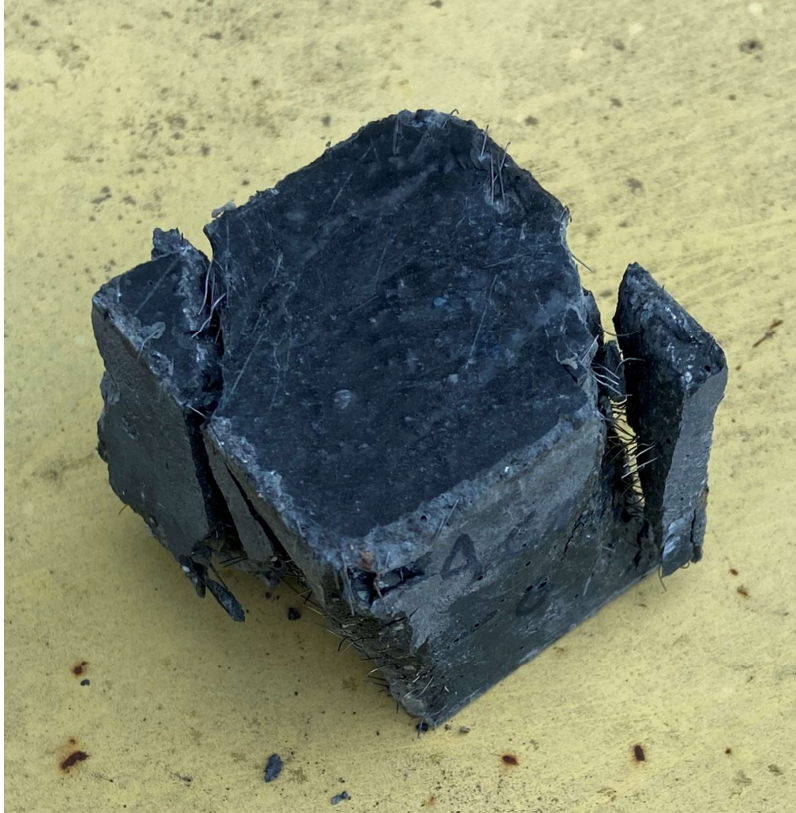


Figure 4-29: 28 Day Composite Specimen Post-Compression (Plan View)

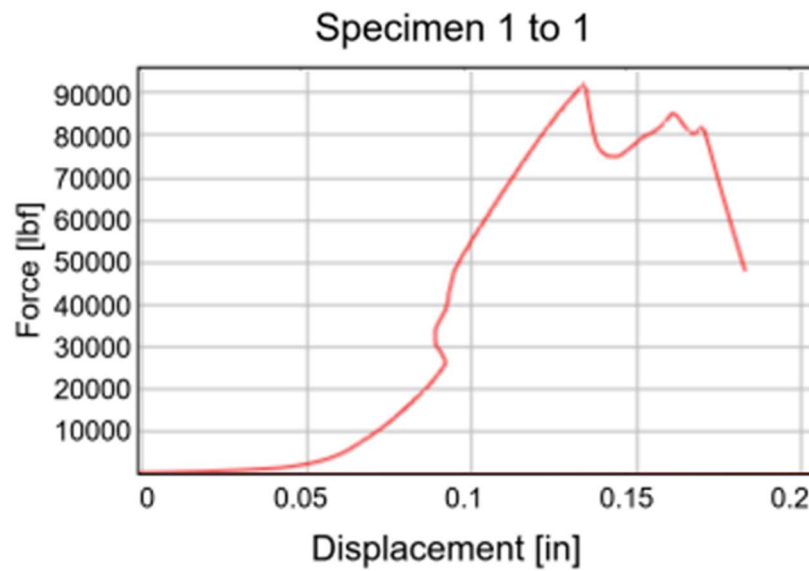


Figure 4-30: Force vs. Displacement of Composite Sample at 14 Days

compressive strength of 22.5 ksi, with a maximum specimen strength of 23 ksi. There were two samples tested in the composite testing, the minimum ordained by ASTM C109. The concrete experienced a less than 2% average strength gain, with no increase in maximum strength after 14 more days of curing. This data suggests that there is not a significant late strength gain in this UHPC. Because of this, the performed study does not support the 14-day approximation, and supports the standard 28-day testing procedure. **Figure 4-31** shows the force with respect to displacement during the procedure for one of the samples.

4.2.4: Surface Resistivity

The surface resistivity of the mixture was measured at 28 and 56 days according to AASHTO T 358. The average apparent resistivity, as well as the geometry corrected resistivity, are displayed in **Table 4-8**. All values are displayed in **Figure 4-32** and **Figure 4-33**. This penetrability is classified as low at 28 days, and very low at 56 days. Low penetrability was expected, due to the optimized gradation and particle size.

4.2.5: Flexural Strength

To be classified as UHPC, the concrete must have notable flexural strength in conjunction with the previously described compressive strength parameters. The small maximum aggregate size relative to common concrete mixes, and the incorporation of fibers, are documented to improve the performance of concrete tensile strength. The concrete was tested according to ASTM C1609, with a specimen of 4 inches by 4 inches by 14 inches. The freshly cast flexural specimen is shown in **Figure 4-34**, and the demolded specimen is shown in **Figure 4-35**.

After 28 days of curing, the sample was tested for flexural capacity. The specimen was tested in the configuration displayed in **Figure 4-36**. The specimen withheld a maximum force of 9967 lb, with a specimen deflection of 0.062 in. This correlates to a flexural strength of 3.27 ksi based on the specimen dimensions. This is significant, as normal-strength concrete typically has a flexural capacity of 0.65-0.85 ksi (Mahadik et al., 2014). A specimen loaded at max capacity is displayed in **Figure 4-37**. The specimen was placed under further loading until the fibers began to separate from the specimen, shown in **Figure 4-38**. The specimen stayed in tact even after the fibers began separating. The loading from the beginning to the end of the experiment, along with the

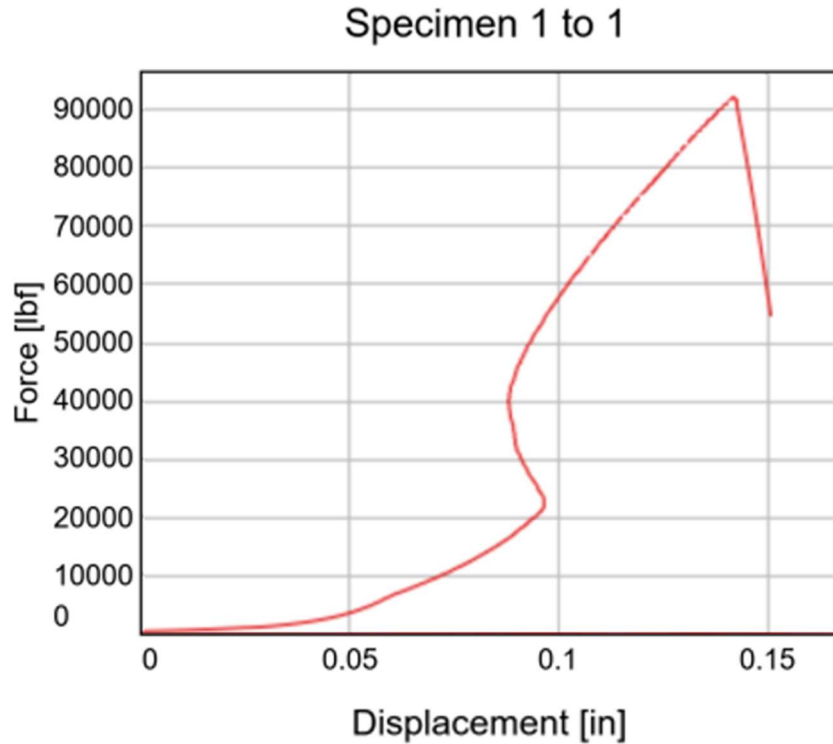


Figure 4-31: Force vs. Displacement of Composite Sample at 28 Days

Table 4-8: Surface Resistivity of UHPC Specimens

Mix ID	28 Day Apparent Resistivity (KΩ-cm)	56 Day Apparent Resistivity (KΩ-cm)	28 Day Corrected Resistivity (KΩ-cm)	56 Day Corrected Resistivity (KΩ-cm)
Ac5	29.63	55.07	15.43	28.68

Mix ID	Elapsed Days	Sample No	Apparent Surface Resistivity (KΩ-cm)							
			0	90	180	270	0	90	180	270 Average
Ac5	28	1	25.30	26.84	29.04	28.38	24.86	27.39	28.38	29.59
		2	31.90	31.35	36.08	31.79	30.14	29.48	33.33	30.14
		3	29.70	29.59	29.59	28.49	29.26	30.14	29.81	30.58
	56	1	54.34	56.54	52.80	54.23	53.90	56.10	51.70	57.53
		2	64.57	58.52	60.39	56.87	59.62	58.08	61.05	54.56
		3	45.87	52.80	52.25	53.02	47.19	52.58	52.58	54.56

Figure 4-32: Apparent Surface Resistivity of UHPC Specimens

Mix ID	Elapsed Days	Sample No	Surface Resistivity (K Ω -cm)								Average
			0	90	180	270	0	90	180	270	
Ac5	28	1	13.18	13.98	15.13	14.78	12.95	14.27	14.78	15.41	14.31
		2	16.61	16.33	18.79	16.56	15.70	15.35	17.36	15.70	16.55
		3	15.47	15.41	15.41	14.84	15.24	15.70	15.53	15.93	15.44
	56	1	28.30	29.45	27.50	28.24	28.07	29.22	26.93	29.96	28.46
		2	33.63	30.48	31.45	29.62	31.05	30.25	31.80	28.42	30.84
		3	23.89	27.50	27.21	27.61	24.58	27.39	27.39	28.42	26.75

Figure 4-33: Corrected Surface Resistivity of UHPC Specimens



Figure 4-34: Fresh UHPC Flexural Specimen



Figure 4-35: Demolded UHPC Flexural Specimen



Figure 4-36: Flexural Test Configuration

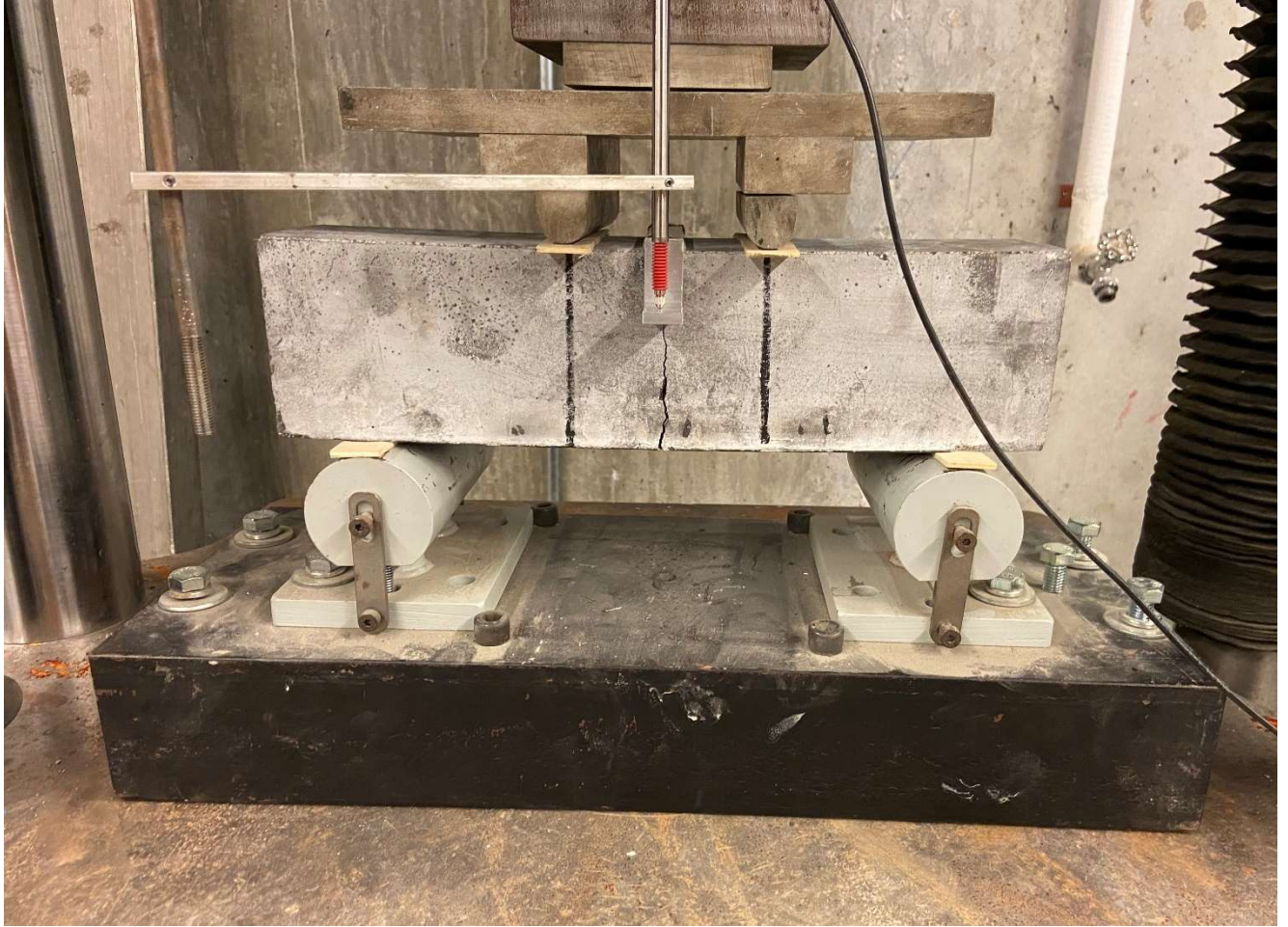


Figure 4-37: Flexural Test at Failure



Figure 4-38: Flexural Test Loaded to Fiber Separation

recommended minimum trend, is displayed in **Figure 4-39**. Flexural strength is 1.3-1.5 times greater than the tensile strength of reinforced concrete (Origen Engineering Solutions, 2019). This correlates to an expected minimum tensile strength of 0.99 ksi for the developed UHPC specimen, greater than the recommended 0.75 ksi tensile strength for UHPC.

The Federal Highway Administration (FHWA) has certain recommendations for UHPC ductility and flexural capacity. The flexural capacity at the first crack (f_{fc}) should be greater than or equal to 1.5 ksi. The ultimate flexural capacity (f_{fu}) should be greater than or equal to 2 ksi, and $1.25f_{fc}$. The final value at the specimen length/150 (f_f) should be greater than or equal to $0.75f_{fc}$. The first crack is found at the first location graphically where the slope is equal to 0. There will be several slope fluctuations in the exported data due to the testing parameters, but the true first crack will be noticeable graphically. The tested UHPC had enough maximum flexural strength to reach the 2 ksi recommendation, however, the first crack was also the maximum flexural strength the concrete could receive. Both of these values occurred before the L/150 threshold for deflection. To improve this undesirable ductility, more fibers would need to be added, whether that be more steel fibers, or a more complex hybrid reinforcement system consisting of carbon fibers or microfibers. A heightened optimization of gradation, and higher percentage of cement in the cementitious mixture, could have lowered the initial deflection. While the tested concrete did not meet the specified threshold for ductile capacity of UHPC, this testing shows that the developed UHPC has significant flexural and tensile capacity, separating it from the normal-strength specimens (FHWA 2024).

4.2.6: High Temperature Performance

For additional durability information, potential fire-resistance capabilities were tested. Red flames sustain about 600°C temperatures. Using an Isotemp 650 Series Model 58 Muffle Furnace, concrete cylinders were heated at 600°C for one hour. The furnace, located in a separate facility, was heated to 600°C before the specimens were placed inside. **Figure 4-40** displays the concrete in the furnace prior to heating. All concrete cylinders cured for 28 days prior. The UHPC composite was heated in the furnace, as well as A-LS1-MS-0, as A-LS1-MS-0 displayed the highest compressive strength at 28 days of the normal-strength mixes. After an hour of

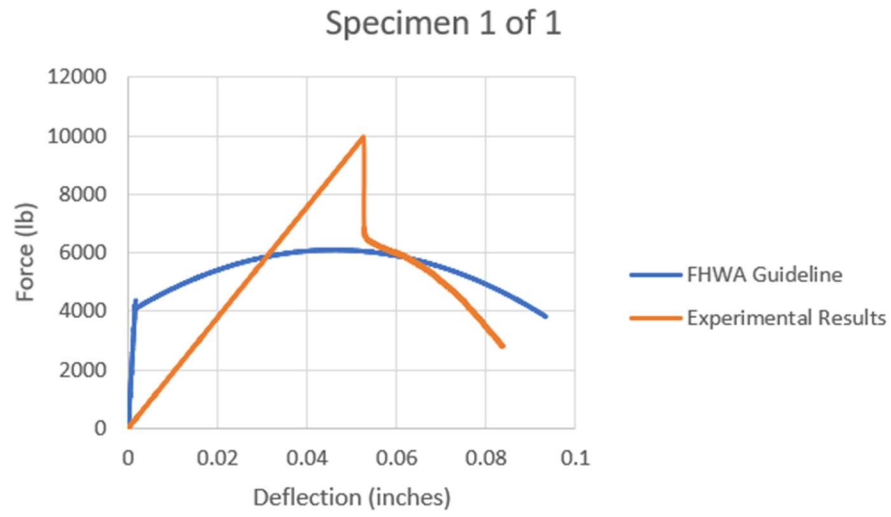


Figure 4-39: Force vs. Displacement of Composite Sample (Flexural Test)



Figure 4-40: Concrete Cylinders in Furnace

heating, the concrete was allowed to air-cool on a rack. The UHPC after cooling is shown in **Figure 4-41**. Spalling occurred in the UHPC specimens, with exterior cracks significantly more visible than in the normal-strength concrete. A close-up image of this phenomenon in Ac5 is shown in **Figure 4-42**. This is attributed to the steel fibers expanding due to the intensity of the heat, increasing the internal stresses (Khoury, 2000).

The concrete specimens were then tested in compression after the furnace heating. This process followed the previous cylinder compression procedures. **Figure 4-43** displays A-LS1-MS-0 after compression, while **Figure 4-44** displays Ac5 after compression. **Table 4-9** shows the results from the compression tests, and the comparison to the 28-day strength values. This comparison is explored in the following section.

4.2.7: Section Summary

Ultra-High Performance Concrete was developed that reaches the necessary strength requirements in order to be compared to previously developed normal-strength concrete. Several concrete matrices were created to find an optimal compressive strength. Following the selection of a matrix, a concrete composite was created adhering to UHPC standards. The UHPC was tested to verify these strength requirements were met. Durability testing was also conducted, in the form of fresh property testing, SAM testing, and surface resistivity testing.



Figure 4-41: UHPC Cooling on Racks



Figure 4-42: Spalled UHPC Surface



Figure 4-43: A-LS1-MS-0 Post-Compression After 600°C Heating



Figure 4-44: Ac5 Post-Compression After 600°C Heating

Table 4-9: Compressive Results Due to Heating

Mix ID	Average 28-Day Compressive Strength (ksi)	Average 28-Day Compressive Strength after 600°C Heating (ksi)	Percent Strength Decrease
A-LS1-MS-0	5.92	1.99	66.39
Ac5	23.00	5.54	75.91

Chapter 5: Discussion of Testing Results

Ultimately, UHPC is designed for a different purpose than typical concrete, so vast differences are expected. While normal-strength concrete is designed for efficiency, economic benefits, and sometimes environmental impact, Ultra-High Performance Concrete is made with the sole purpose of mechanical property superiority. From this perspective, UHPC should outclass typical concrete in most strength testing parameters (Park et al., 2022).

A-LS2-NS-0 is the most standard of the tested Class A mixtures. This is due to its utilization of natural sand and its lack of cement reduction. Its composition is displayed in **Figure 4-8**. While all mixes will be compared in some capacity, A-LS2-NS-0 will be the main mixture referenced with the UHPC.

The differences in the concrete performances resides in their makeup of components. A-LS2-NS-0 contained 78.34% of aggregate by weight, 27.37% consisting of coarse aggregate, 17.83% consisting of intermediate aggregate, and 33.14% consisting of fine aggregate. This starkly contrasts with the 32.35% of sand used in mixture Ac5. The sand alone has a larger percentage of weight in this Class A mixture than the chosen UHPC mixture, although this is not true of all of the Class A mixtures. The UHPC had a higher total percentage of water than the typical concrete mixtures (10% in Ac5, 7% in A-LS2-NS0), but a lower water/cement ratio (w/c) and an even lower water/cementitious material ratio (w/cm). Consisting of a high cement percentage is often a component of UHPC. The water/cement and water/cementitious material ratios of A-LS2-NS-0 and Ac5 are displayed in

. The water/cementitious material ratio considers the ratio of water with all binders: cement, natural pozzolans, and mineral admixtures. Cement, fly ash, and silica fumes are all considered cementitious materials in this context. Air entrainer was a material used solely in the Class A mixtures, whereas silica fume and steel fibers were solely used in the UHPC. Silica fume was incorporated to improve the particle packing density of the mixture, while steel fibers added tensile and flexural capacity, as well as combatted the brittleness of the concrete (Du et al., 2021).

From a performance perspective, the UHPC had a complete advantage in strength. While the fibers did add to the compressive capabilities of the UHPC, the matrix itself was stronger than

Table 5-1: Water/Cement and Water/Cementitious Material Ratios

Mixture	w/c	w/cm
A-LS2-NS-0	0.656	0.492
Ac5	0.254	0.185

any of the Tennessee mixes. This is due to the low water/cement ratio and compaction from improved gradation. The UHPC also had flexural strength capacity due to the fibers. The UHPC being superior in all strength categories was expected.

In regard to potential freeze-thaw performance, the normal-strength concrete was designed to have an air content value of 6%. Typically, values above 4% are seen as good for freeze-thaw durability, since the air bubbles leave space for the water to expand and contract without having to damage the concrete. The UHPC had an air content value of 0.5%, which typically would be seen as detrimental to the concrete, as the water that gets into the concrete would have limited room to expand without pressuring the concrete. This was expected due to the density of the mixture. This could have been increased with air-entraining admixture, but the UHPC was made specifically for its mechanical performance. Despite this low air content, the UHPC had a SAM number of 0.27, which qualifies it as acceptable. This is very comparable to the A-LS2-NS0 mixture, which resulted in a SAM number of 0.26. A SAM number of this value means that the air bubbles in the mixture are dispersed at an acceptable level in the UHPC to provide similar freeze thaw performance to that of a normal concrete mixture with an air content of 6.3%. However, the UHPC SAM number was greater than most of the normal-strength concrete values without error, meaning less durability against freeze-thaw due to air bubble dispersion. Despite the density of the mixture could affect the size and frequency, that did not lead to improved dispersion of the air bubbles present.

The penetration from surface resistivity was measured with both the normal-strength concrete and the UHPC. For most of the normal-strength concrete samples, including A-LS2-NS0, the resistivity values reached the moderate threshold at 28 days, then the low threshold at 56 days. Ac5 reached the low threshold at 28 days, followed by the very low threshold at 56 days. These values would be expected to increase at a less than linear trend until 91 days, so none of the specimens would presumably surpass the very low threshold of 254 K Ω -cm. Based on the experimental results, UHPC should result in less surface penetration, which would provide more resistance to chemical seepage and weathering. It also should reduce the amount of water entering the specimen, however, this is not the only information necessary to adequately gauge resistance to freeze-thaw. Ultimately, water will still penetrate the specimen unless it passes 254

K Ω -cm to reach the negligible penetration tier. With this information, it is important to couple the surface resistivity data with the SAM number information. A specimen with very low penetration (37-254 K Ω -cm) and good SAM value (0.2-0.3) would not necessarily provide better freeze-thaw durability than a specimen with low penetration (21-37 K Ω -cm) and excellent SAM value (less than 0.2).

Considering high-temperature durability, all Portland-cement based concrete is expected to be damaged in the presence of 600°C heat, and thus lose strength (Khoury, 2000). In this study, the UHPC specimen saw a 75.91% decrease in compressive strength (23.00 ksi to 5.54 ksi), while the normal strength concrete saw a 66.39% decrease in compressive strength (5.92 ksi to 1.99 ksi). Normal strength concrete is expected to lose roughly 60% of its strength (Wróblewska & Kowalski, 2020). This loss still leaves UHPC with a greater compressive strength after fire, but the greater loss is significant, as concrete is not designed for such losses in strength. The UHPC also had visible exterior cracking due to the temperature change, which the normal strength concrete did not. This testing shows that it is possible for UHPC to be less durable than normal concrete in the presence of fire.

Scanning Electron Microscopy analysis was conducted to provide further backing to the durability results. The UHPC matrices were analyzed after compressive failure to provide data on its homogeneity, pore patterns, and microcracking, all of which affect the permeability and freeze-thaw resistance of the concrete. The UHPC was analyzed after breaking, as opposed to sawing/cutting, as it provides a more accurate interior visual than slicing through the natural formations in the concrete. The matrix was also tested, as opposed to the composite, as the fibers were not essential to this investigation, and their presence could create gaps after the conduction of the compression test. The SEM images were taken at 500-1000 times magnification, with the concrete placed 100 μ m away from the image collector. The exterior of the UHPC was relatively homogenous. An example image can be seen in **Figure 5-1**. The UHPC is somewhat rough, but this is expected of most non-polished concrete. There are very few gaps caused by disproportionate aggregate sizes, which verifies the success of the gradation. However, there are still varying sizes of pores in this concrete. In **Figure 5-2** and **Figure 5-3**, the interior of the concrete can be seen. These images verify the fine granularity level consistently throughout the

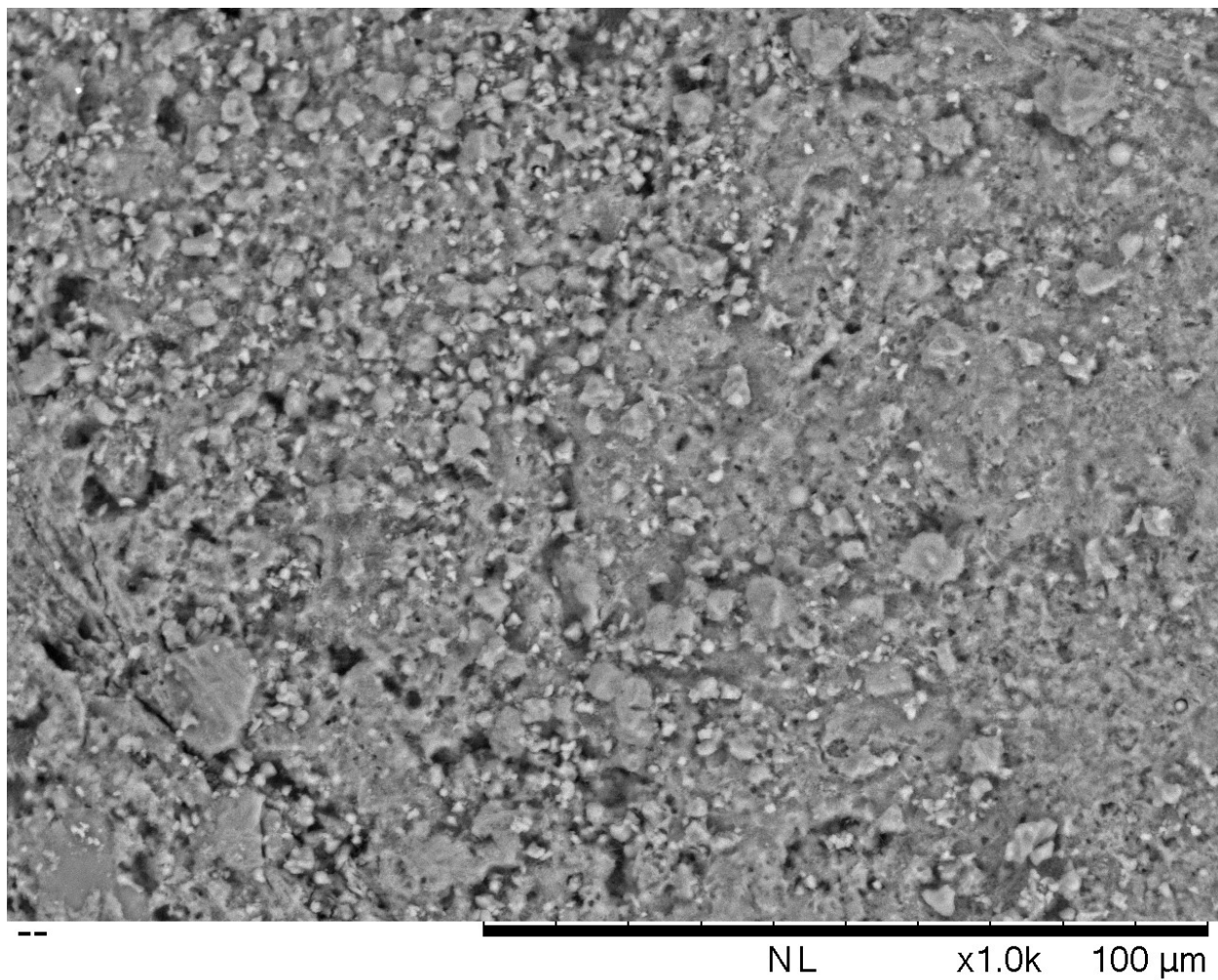


Figure 5-1: Exterior SEM Image of UHPC Specimen

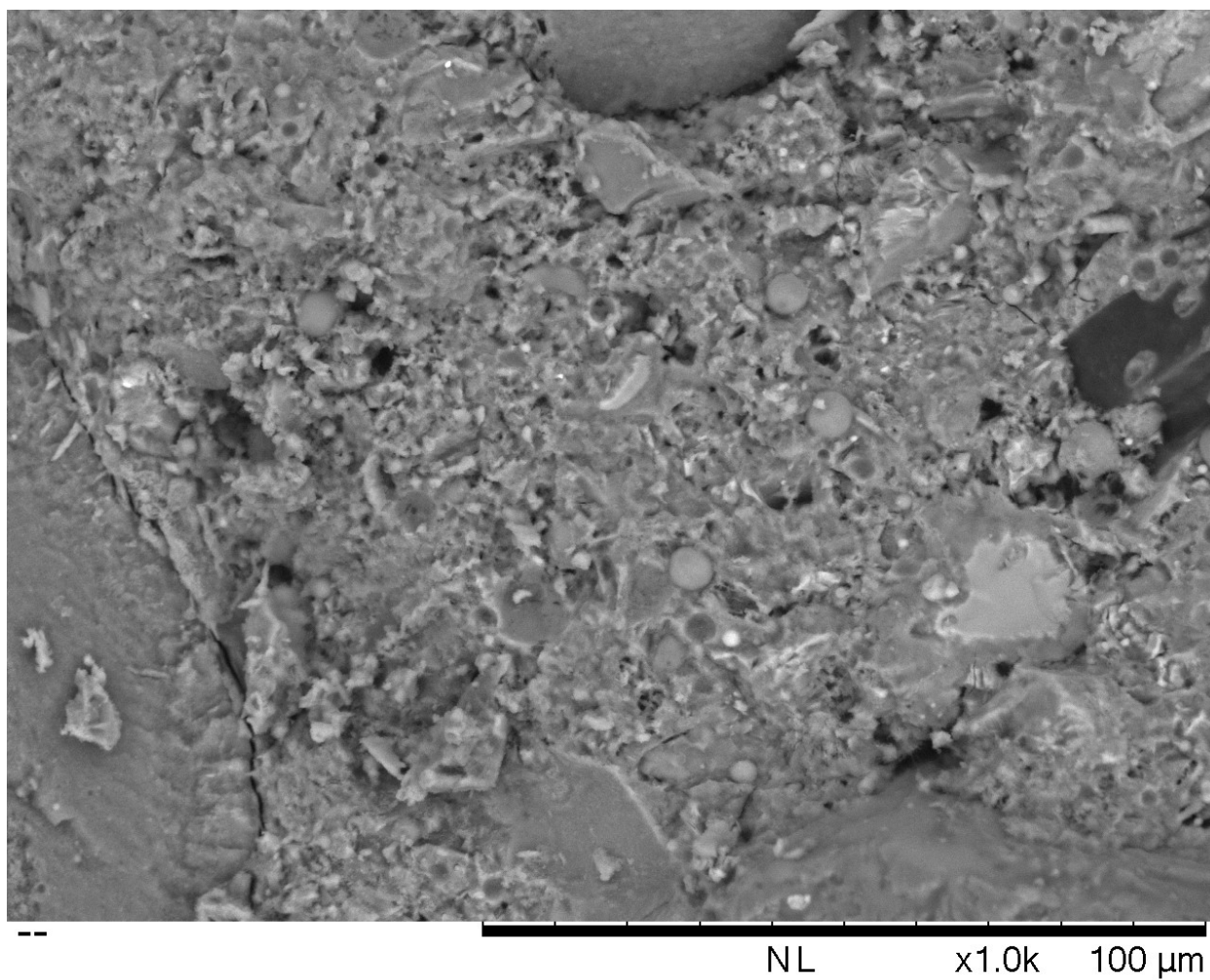


Figure 5-2: Interior SEM Image of UHPC Specimen

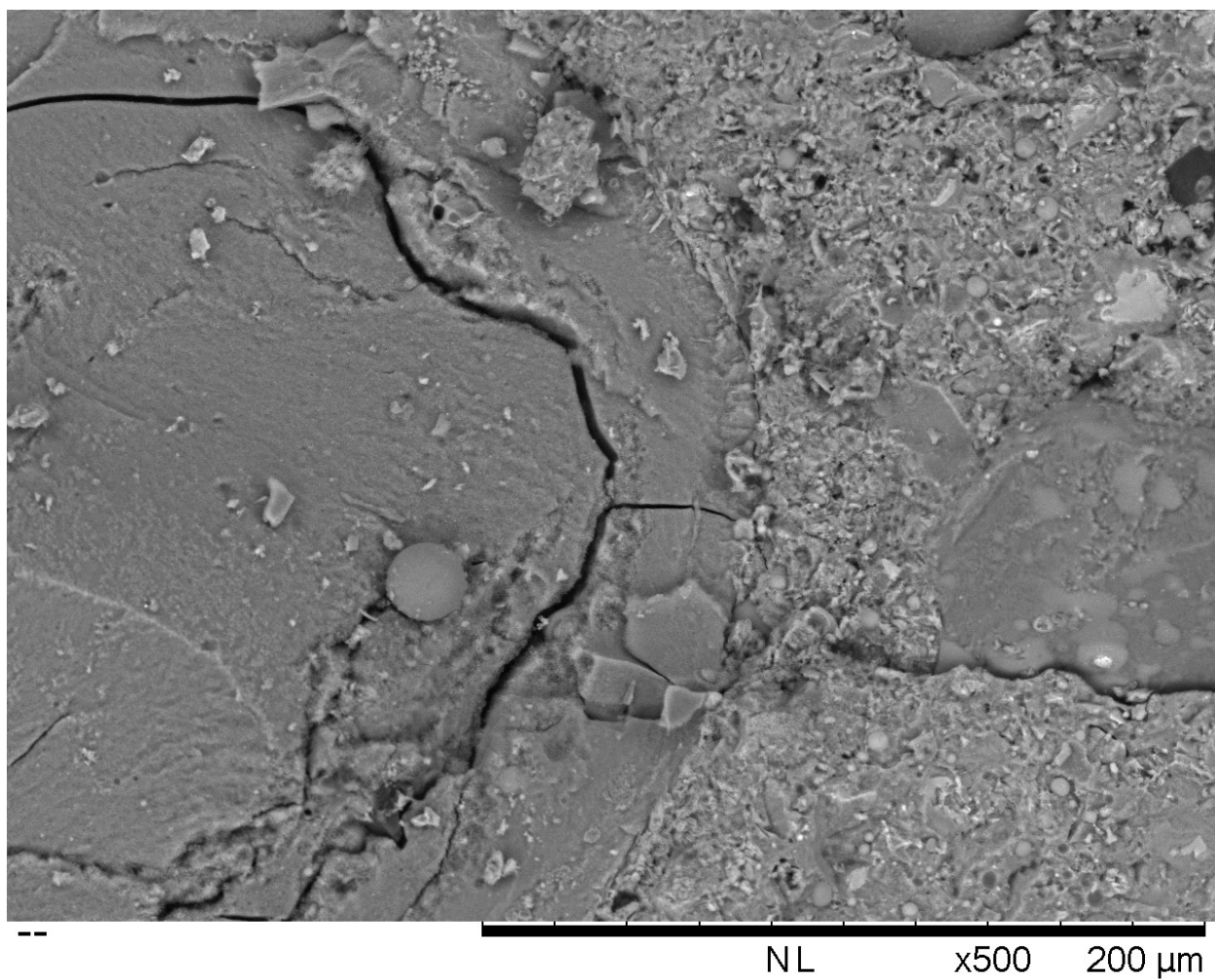


Figure 5-3: Interior Microcrack of UHPC Specimen

concrete. There are smooth, continuous surfaces that can be seen, and those are caused by the breaking of the concrete, evidenced by the large cracks formed near the smooth surfaces. The crack width and depth also is an indication of these measures. These locations indicate higher hydration levels of cement, consistent with initial breakage. On the rougher surfaces, the pores can be seen similarly to the exterior, as well as the small, spherical shapes of fly ash particles, and the larger, darker formations of CH compounds, typical of pozzolan reactions (Diamond & Huang, 2001). While the large cracks are due to the compression testing, the smaller cracks, while still influenced by compression, are caused by the shrinkage of concrete over time. These cracks are visible on the exterior, which shrinks faster, and the interior, which contributes to the concrete's permeability (Grassl et al., 2010). **Figure 5-4, Figure 5-5, Figure 5-6, Figure 5-7,** and **Figure 5-8** show other relevant SEM images regarding interior and exterior patterns and conditions. The evidence of nonporous areas in conjunction with porous areas creates both protection against permeation, yet space for water expansion, aiding in the overall freeze-thaw durability.

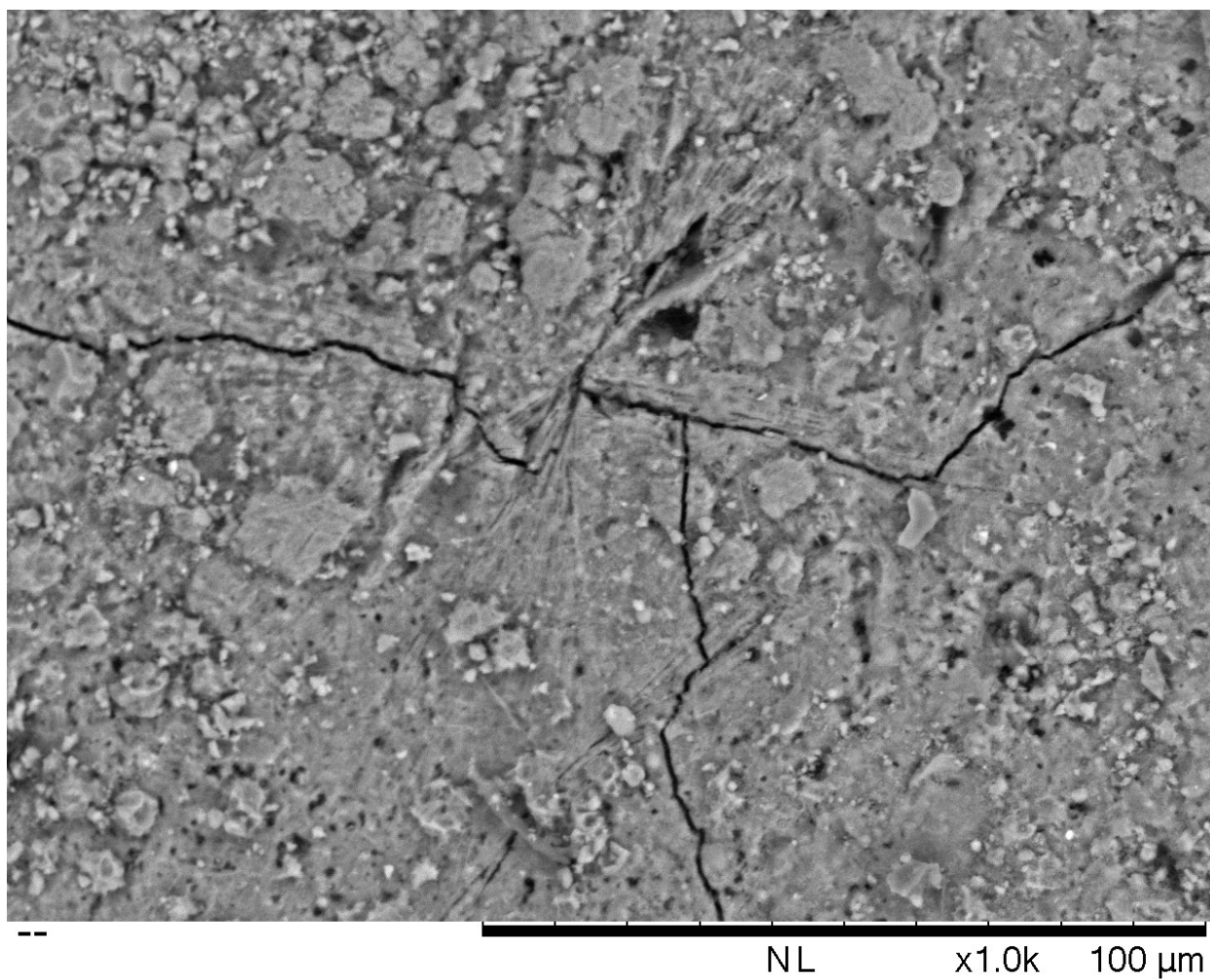


Figure 5-4: Exterior Microcrack of UHPC Specimen

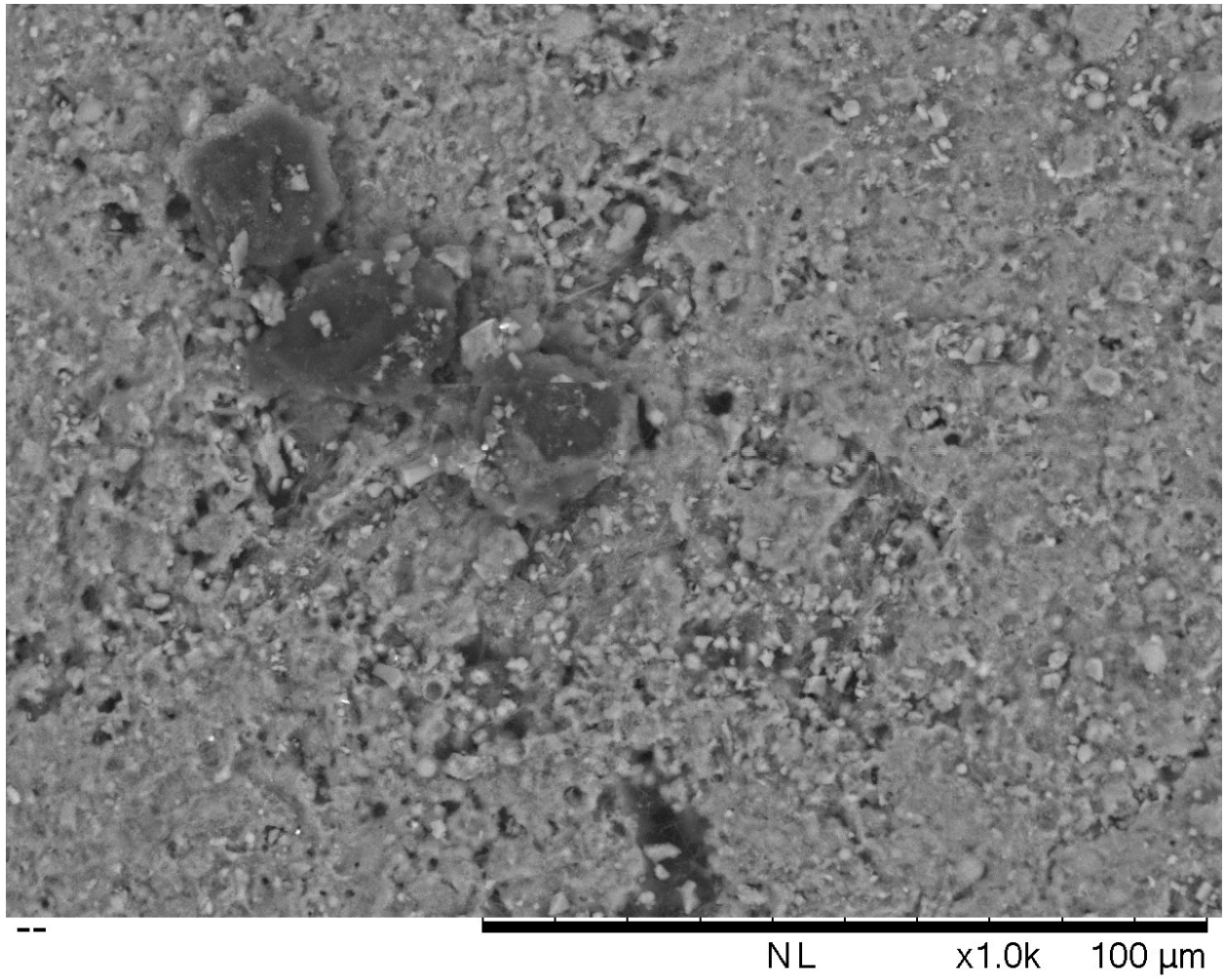


Figure 5-5: Exterior Coarse Entity in UHPC Specimen

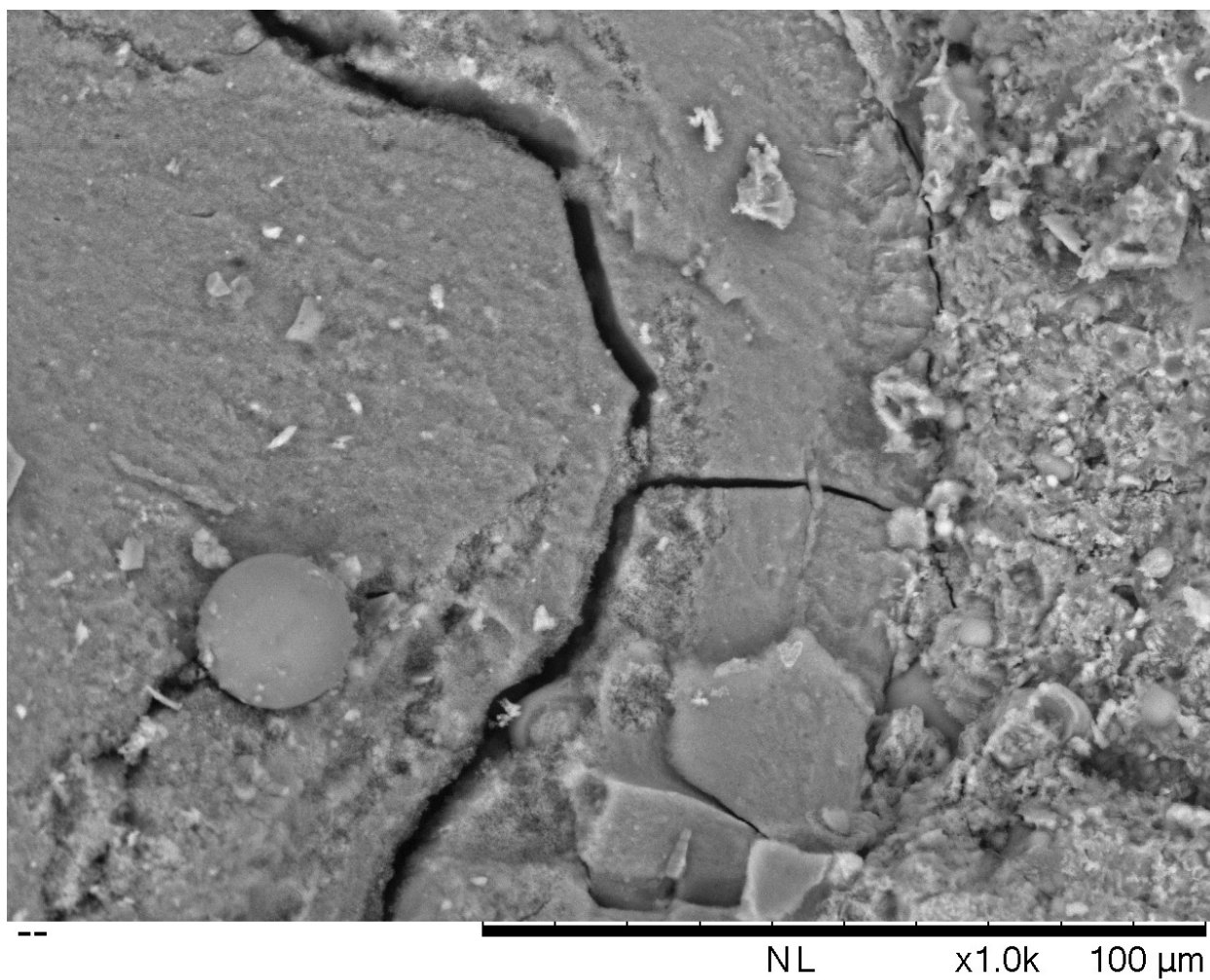


Figure 5-6: Interior Microcrack of UHPC Specimen (1000x Magnification)

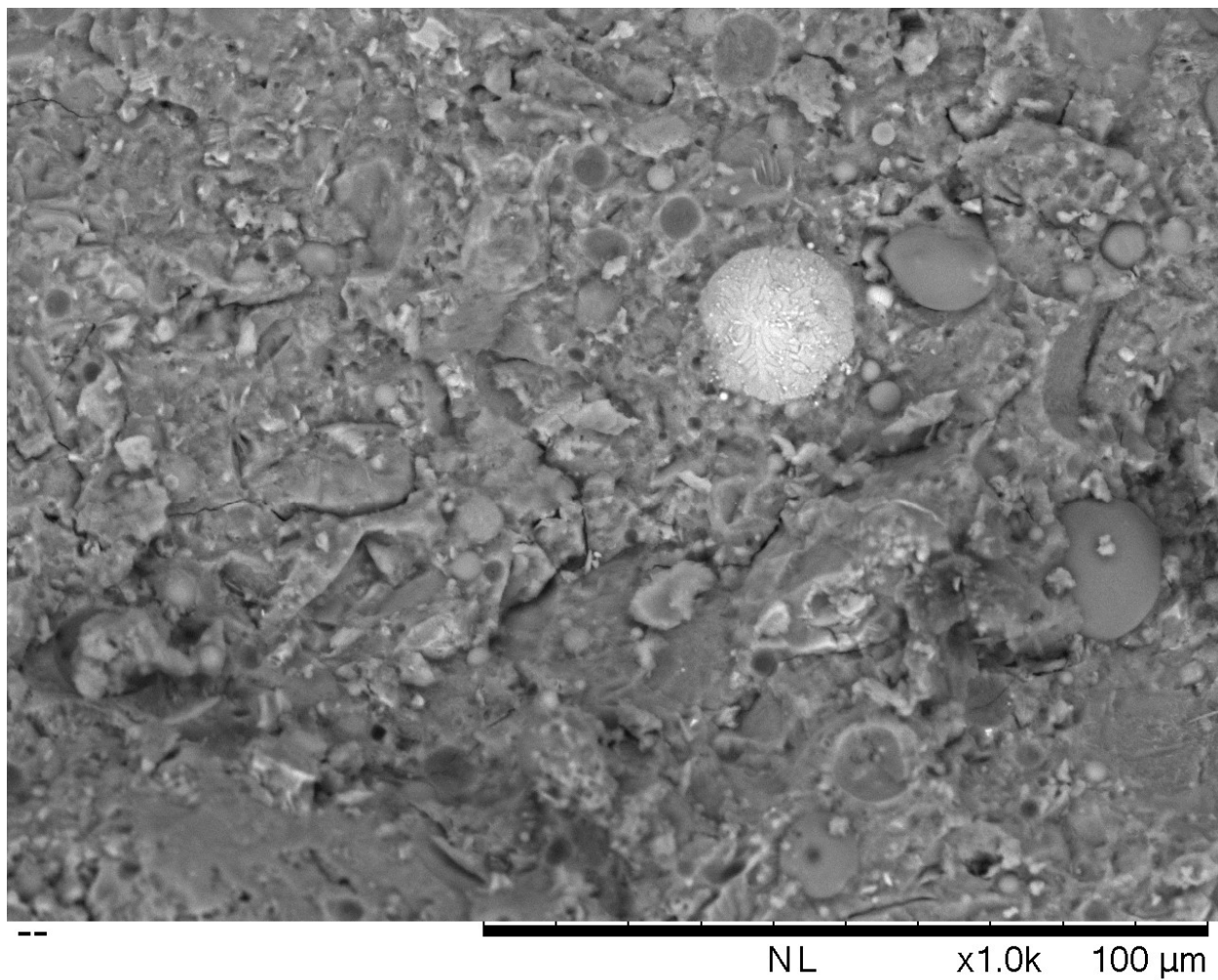


Figure 5-7: Interior Coarse Entity in UHPC Specimen

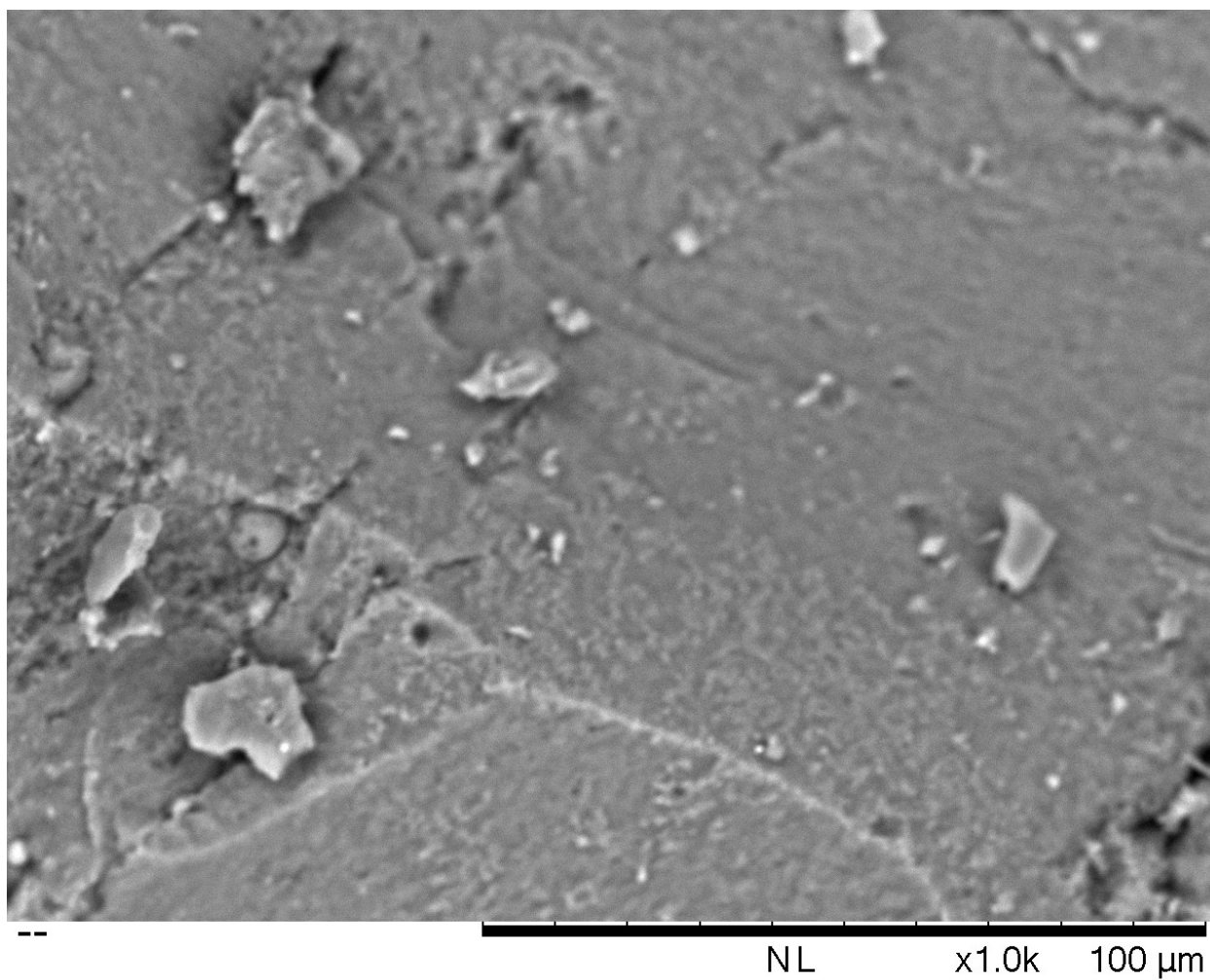


Figure 5-8: Nonporous Interior of UHPC Specimen

Chapter 6: Conclusion

A comprehensive study on the comparison between normal-strength concrete and Ultra-High Performance Concrete, specifically in durability capacity, was exercised. The design of the mixtures, as well as the testing procedures enacted, were considered in high detail according to their ingredients and possible performance outcomes. The corresponding results of the concrete formed were noted, analyzed and compared to produce understanding of their makeup and properties. From the study, the following can be concluded:

- Without the specified use of air-entrainer, UHPC will typically have less air content than normal-strength concrete. The mix design emphasizes smaller particles and optimized gradation, leading to a reduction in voids to improve overall strength. This lower air content usually results in lower performance in freeze-thaw durability.
- The SAM test performed in the study resulted in an acceptable SAM number for the developed UHPC mixture. The normal-strength concrete produced great, acceptable, and unacceptable SAM numbers. This shows that UHPC can be better or worse than normal-strength concrete in void spacing for freeze-thaw.
- UHPC will typically display better penetration resistance from surface resistivity. While there still are voids, as shown in the SEM imaging, the voids are smaller and there are less, due to the density of the mixture. This does lead to better durability regarding chemical penetration and freeze-thaw resistance.
- The UHPC in the study displayed a greater reduction in strength in the presence of red fire-like conditions than the normal-strength concrete. This large reduction still leaves the UHPC with a stronger compressive strength than normal-strength concrete in the same conditions, but the larger strength reduction is more concerning in building design applications. Concrete with steel fibers will always have higher internal pressure under fire, which leads to spalling and significant cracking.

- UHPC can be regarded as more durable than normal-strength concrete in penetration resistance due to its higher surface resistivity. Any other claims about UHPC being more durable are potentially true, but not true in every situation. The results of this study cannot support the ideas that UHPC displays better freeze-thaw durability or fire durability than normal-strength concrete. There are even situations where UHPC is less optimal in those categories.
- UHPC has the potential to be more durable than normal-strength concrete, but without further definition and regulation, it can not be considered more durable in general. There would need to be requirements on minimum air-content and maximum SAM number, as well as equivalent fire-resistance, possibly from a maximum steel fiber limit.

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Vita

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