Freeze-Thaw Durability Requirements for New Concrete Structures in Alabama

by

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Abstract

Concrete is one of the most widely used building materials in Alabama Department of Transportation (ALDOT) infrastructure. Section 501, "Structural Portland Cement Concrete," of the *ALDOT 2026 Standard Specifications for Highway Construction* specifies a required total air content range of 2.5 to 6.0% that is intended to ensure that concrete mixtures are protected from freeze-thaw damage. However, the total air content is the sum of both entrapped and entrained air voids and does not provide a measure of the internal spacing of the entrained air voids that protect the concrete from freeze-thaw damage. Given this limitation, a new test method called the Sequential Pressure Method, also known as the Sequential Air Method (SAM), provides an indication of the quality of the air-void system before the concrete hardens. The adequacy of the SAM for use in ALDOT projects along with the sufficiency of ALDOT Section 501's current required total air content range are evaluated in this project.

A literature review and a laboratory testing phase were conducted to determine the mixture proportion factors that influence the freeze-thaw resistance of concrete mixtures. A meta-analysis of literature-derived data was also performed using multivariable linear regression analysis, logistic regression analysis, and classification analysis. The classification analysis was repeated for data obtained from laboratory testing. In the laboratory testing phase, 34 concrete mixtures with water-to-cement ratios of 0.35, 0.40, 0.45, and 0.50 and total air contents of 2.0 to 7.0% were tested. It was found that the current ALDOT required minimum total air content is too low to protect concrete from freeze-thaw damage and the allowable range of total air contents should therefore be increased to 3.5 to 7.0%. It was also found that there is no benefit

of using the SAM as opposed to the current total air content test for quality assurance testing to identify non-freeze-thaw durable concrete mixtures in the field. The SAM is therefore not recommended for implementation by ALDOT.

Artificial Intelligence (AI) Use Disclosure Statement

In the preparation of this thesis, the following Artificial Intelligence (AI) tools were used: Elicit, Consensus, ChatGPT, Gemini, and Claude. These tools were used for several purposes. Elicit and Consensus were used to find journal articles relating to freeze-thaw damage of concrete and to provide a summary of the major findings of each article. Once an article or source was deemed relevant, the original source was downloaded and reviewed. ChatGPT and Gemini were used to teach the author Microsoft Excel functions and to find Excel add-ins that were used in the multivariable linear regression analysis and logistic regression analysis. They were also used to teach the author how to perform certain tasks on Microsoft Word such as setting up multilevel lists. Claude was used to organize quotes by research topic from research compiled on an Excel spreadsheet into a Word document. The Word document was a preliminary draft of the literature review that was then reviewed and revised by the author. Claude was also used to generate a choropleth map. The author acknowledges full responsibility for the intellectual content of this work and has ensured that all AI-assisted sections have been reviewed and revised for accuracy and appropriate academic style. All AI-generated content was reviewed and validated for relevance, appropriateness, and accuracy before incorporation into the final document to maintain scholarly integrity of this research.

Digital Accessibility Disclosure Statement

In the preparation of this thesis / dissertation, the following digital accessibility tools were used to ensure this document complies with federal requirements: Microsoft Word Check Accessibility Function. The author acknowledges full responsibility for the intellectual content of this work and has made a good faith effort to comply with digital accessibility requirements in publishing, wherein the nature of the content does not significantly change in order to do so. Furthermore, all content has been reviewed and revised to meet these requirements prior to final publication.

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CHAPTER 1

INTRODUCTION

1.1 Background

Ensuring the long-term durability of concrete structures exposed to cycles of freezing and thawing while it is wet is essential to produce long-lasting infrastructure in Alabama. If proper measures are not taken to protect the concrete from damage caused by exposure to cycles of freezing and thawing, hereafter called freeze-thaw damage, infrastructure can deteriorate well before the end of its intended service life. One form of this deterioration includes surface scaling which results in changes of appearance, surface smoothness, and in severe cases, loss of concrete cover over reinforcing steel. Other forms of freeze-thaw deterioration include internal microcracking resulting in loss of structural integrity, disintegration, and potential delamination of concrete in cases of freeze-thaw damage at early concrete ages (ACI 201.2 2023). This deterioration necessitates expensive and driver-delay-inducing closures to repair and in severe cases, replacement of the damaged concrete structure.

The primary way in which concrete infrastructure can be protected from freeze-thaw damage is by ensuring that it has an adequate air-void system that allows hydraulic and osmotic pressures that develop as a result of internal freezing of pore water to be relieved by providing an escape for freezing water (Powers 1949; Powers and Helmuth 1956). One way of determining the total amount of voids present in the air-void system is by measuring the fresh total air content using a Type B pressure meter in accordance with AASHTO T 161 (2024). Another way of determining the total air content is to use a Sequential Air Method (SAM) meter. The SAM meter measures the total air content and also determines a Sequential Air Method (SAM) number that is intended to provide an indication of the spacing of the internal air voids of the cement paste. The method of test for determining the total air content and SAM number using the SAM meter is described in AASHTO T 395 (2024). Both the Type B pressure meter and the SAM meter are shown in Figure 1-1 for comparison.

Figure 1-1. (*left*) Type B Pressure Meter and (*right*) Super Air Meter (SAM)
(Source: Gilson Company 2023)

The total air content consists of both entrapped and entrained air voids. Entrapped air voids are large air voids that are spaced far apart that remain left over after the concrete has been consolidated due to the consolidation processes' inability to remove them. Entrapped air voids are normal and consist of approximately 1.5 to 2.5% of the concrete volume in most bridge deck applications. Entrained air voids are microscopic voids that are added to the concrete by the use of an air-entraining admixture. Currently, Section 501 of the *ALDOT 2026 Standard Specifications for Highway Construction* (2026), hereafter referred to as ALDOT 501, requires a total air content of 2.5 to 6.0% for most concrete infrastructure. The importance of using an air-entraining admixture can be seen in Figure 1-2, which shows that concrete mixtures that are not air-entrained can experience significant freeze-thaw damage at an early age compared to air-entrained concrete mixtures. The importance of the total air content can also be derived from the figure since concrete mixtures with higher total air have good freeze-thaw performance whereas concrete mixtures with lower total air contents have poor performance.

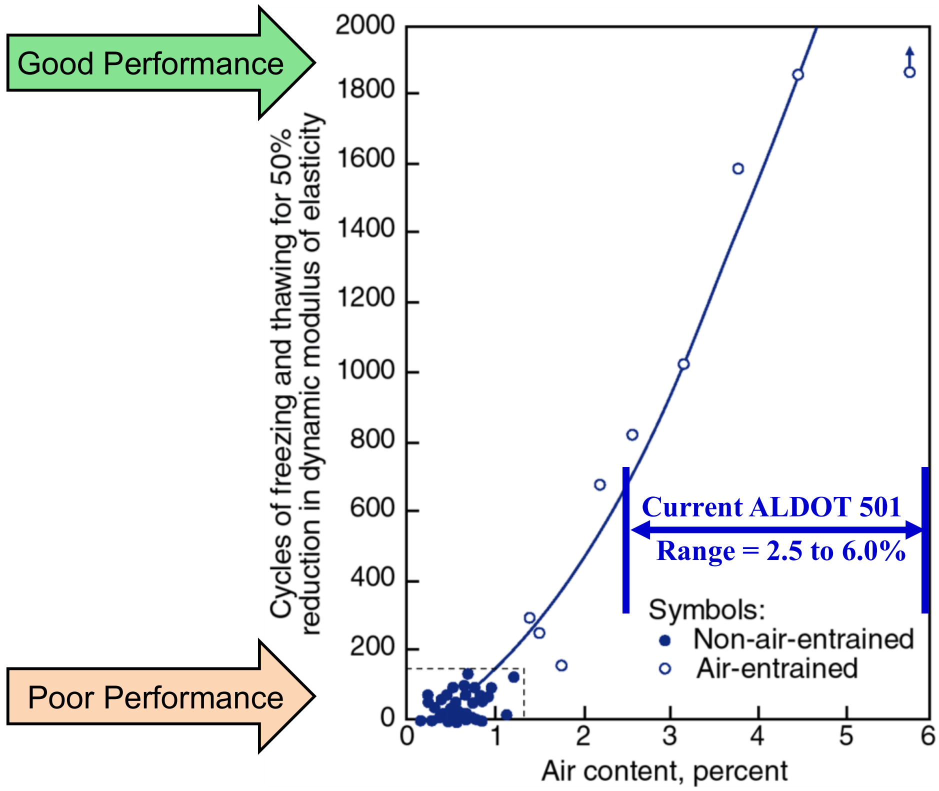


Figure 1-2. Effect of Entrained Air on the Resistance of Concrete to Freeze-Thaw Damage [adapted from Lerch (1960) and Bates et al. (1952)].

Figure 1-3 portrays the difference in performance over the course of 40 years of two concrete weathering blocks exposed to cycles of freezing and thawing with the one on the left being non-air-entrained and the one on the right being air-entrained. The non-air-entrained concrete block has disintegrated while the air-entrained concrete block has suffered minimal damage. The importance of the total air content is also emphasized by the results in Figure 1-4, which suggest that a total air content of at least 3.5% is required to ensure an adequate level of freeze-thaw durability.

(a) (b)

Figure 1-3. Effect of Cycles of Freezing and Thawing on Two Weathering Boxes over the Course of 40 Years. The box on the left (a) is non-air-entrained while the box on the right (b) is air-entrained. (Kosmatka et al. (2002).

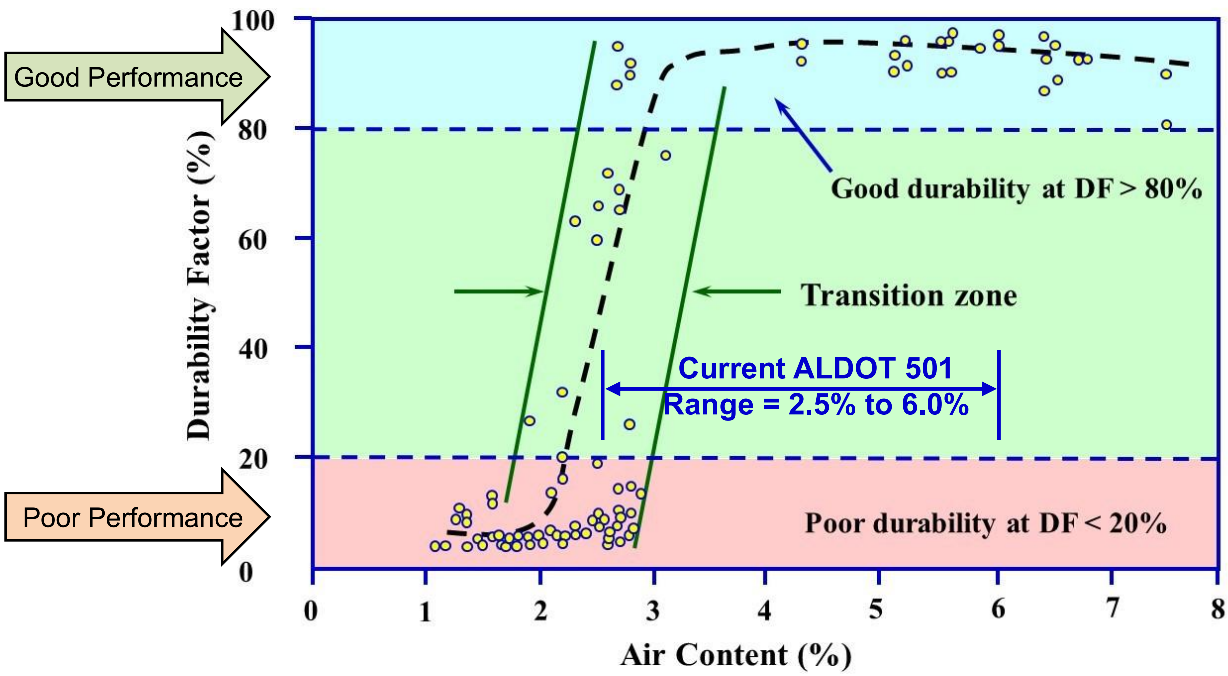


Figure 1-4. Durability Factors at End of Freeze-Thaw Test versus Total Air Content [adapted from Newlon and Mitchell (1994)].

A concrete mixture's potential freeze-thaw resistance is measured by its durability factor as determined in accordance with AASHTO T 161 (2022). In AASHTO T 161, concrete prisms that have been moist cured for 14 days are exposed to 300 cycles of freezing and thawing in a freeze-thaw test cabinet, such as the one shown in Figure 1-5. In Procedure A, the prisms are covered with water throughout the test. At a maximum frequency of at least every 36 cycles, the prisms are removed from the cabinet and tested to determine their relative dynamic modulus of elasticity (RDME), which gives a measure of the internal soundness of the prisms relative to their initial condition. At the end of 300 freeze-thaw cycles, the durability factor, a function of the RDME, is reported with a durability factor of 60 being considered acceptable (Newlon 1978) and a durability factor of 80 being considered excellent (Obla et al. 2016).

Figure 1-5. Freeze-Thaw Cabinet used for AASHTO T 161 Testing.

(adapted from Humboldt Manufacturing Company 2023).

1.2 Research Objectives

The main goals of this research were to evaluate the appropriateness of the ALDOT Section 501 required total air content range of 2.5 to 6.0% for concrete classes A through D, determine the ability of Type B pressure meter total air content results and SAM number results to identify concrete mixtures that are non-freeze-thaw durable, and if needed, to recommend new specification requirements designed to ensure ALDOT concrete mixtures are freeze-thaw durable. The results from this research are intended to provide ALDOT with research-based guidance regarding its quality assurance practices that are aimed at ensuring newly constructed concrete infrastructure is freeze-thaw durable. The primary tasks of the research conducted by Auburn University to reach the project objectives were:

- Perform a literature review to understand current research regarding freeze-thaw damage of concrete mixtures,
- Perform laboratory testing to determine the freeze-thaw resistance of typical ALDOT concrete mixtures,
- Determine if the current required total air content range of 2.5 to 6.0% is adequate to protect concrete from freeze-thaw damage,
- Determine if the Type B pressure meter or the SAM should be used to evaluate the freeze-thaw resistance of ALDOT concrete mixtures
- Determine the effects of mixture proportions on the freeze-thaw resistance of ALDOT concrete mixtures.

1.3 Research Methodology

To achieve the objectives stated in the previous section, a three-stage research plan was developed. In stage one, literature was reviewed to understand the theories of the mechanisms causing freeze-thaw damage, prerequisites of freeze-thaw damage, the role of air-entrainment in providing freeze-thaw resistance to concrete mixtures, indicators of freeze-thaw durability, other factors affecting freeze-thaw durability, and current freeze-thaw resistance guidance.

In the second stage, a meta-analysis of literature-derived data was performed. In this analysis, 391 sets of concrete testing results were obtained from six literature sources that were analyzed by three methods: multivariable linear regression analysis, logistic regression analysis, and classification analysis. The multivariable linear regression analysis and logistic regression analysis were performed to determine which factors affect the freeze-thaw resistance of ALDOT concrete mixtures and what is the magnitude of their impact. The classification analysis was performed to establish relationships between indicators of freeze-thaw durability and the durability factor, and to determine the optimized total air content. The author defines the optimized total air content as the total air content that accomplishes the dual goals of minimizing the volume of non-freeze-thaw durable concrete that is accepted and placed in the field while minimizing the volume of freeze-thaw-resistant concrete that is rejected.

In the third stage, 34 concrete mixtures meeting the requirements of ALDOT 501 Classes A and B and ALDOT 513 concretes were produced and tested. However, some mixtures intentionally had total air contents that were either below or above the current 2.5 to 6.0% requirement in ALDOT 501. All mixtures were made using Type IL cement and had water-to-cement ratios (w/cm) of 0.35, 0.40, 0.45, and 0.50. The w/cm of 0.35 mixtures were designed to meet the requirements of ALDOT 513 for use in prestressed concrete bridge members and had a

6% dosage of silica fume by weight of cement. The w/cm of 0.40 and 0.45 mixtures were designed to meet the requirements of ALDOT 501 Class B concrete for use in box culverts, bridge substructures, and bridge superstructures. The w/cm of 0.50 mixtures were designed to meet the requirements of ALDOT 501 Class A concrete for use in retaining walls, concrete safety barriers, headwalls, and inlets. Mixtures with w/cm of 0.40, 0.45, and 0.50 had a 30% dosage of Class C fly ash by weight of cement. The results in stage three of the research were also analyzed using a classification analysis.

1.4 Thesis Organization

In Chapter 2, a literature review is presented in which current research related to freeze-thaw damage is discussed. The chapter opens by discussing the theories of the mechanisms causing freeze-thaw damage and prerequisites of freeze-thaw damage. Following this, the role of air-entrainment in providing freeze-thaw resistance to concrete mixtures and the durability factor are presented. Next, indicators of freeze-thaw durability, other factors affecting freeze-thaw durability, and current freeze-thaw resistance guidance are examined.

In Chapter 3, the experimental methods used in this study are presented. An overview of the experimental program is included along with the mixture identification system. Mixture proportions and materials used are provided before concrete production methods are discussed. Lastly, tests performed on fresh and hardened concrete are covered along with curing practices.

The meta-analysis of literature-derived data is discussed in Chapter 4. Background information relating to the multivariable linear regression and logistic regression analysis techniques used in Chapter 4 is presented. Next, sources of data are presented, and the minimum total air content is optimized for target durability factors of 60 and 80. After this, relationships between indicators of freeze-thaw durability and the durability factor are evaluated and discussed. Lastly, the results of the multivariable linear regression analysis and the logistic regression analysis are presented and discussed.

In Chapter 5, the results of laboratory testing are presented and discussed. The optimized total air contents for target durability factors of 60 and 80 are determined. Next, relationships between indicators of freeze-thaw durability and the durability factor are established before the SAM is evaluated for use on ALDOT projects. Lastly, the influence of w/cm, concrete strength, and type of air-entraining admixture on the freeze-thaw durability of the concrete mixtures are examined.

Chapter 6 includes recommended ways to implement the findings of this study by ALDOT.

Chapter 7 covers conclusions and recommendations for future research.

Appendix A includes data analysis results not reported in Chapter 4, and Appendix B presents chemical admixture dosages for each concrete mixture produced and testing in this study. Lastly, Appendices C and D present fresh and hardened concrete testing results, respectively, not included in Chapter 5.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

Ensuring the long-term durability of concrete structures exposed to repeated cycles of freezing and thawing is an essential task in maintaining Alabama infrastructure, because this will minimize expensive and time-consuming concrete repairs and/or replacements, minimize driver delays, and improve performance. Because bridges, pavements, and prestressed concrete members are designed to remain in service for decades, concrete that deteriorates prematurely due to cycles of freezing and thawing imposes maintenance and replacement costs well before the end of the intended design life is reached. Damage caused by cycles of freezing and thawing manifests as internal microcracking, surface scaling, loss of mass, and in severe cases, delamination, all of which compromise the structural capacity and serviceability of affected concrete elements (ACI 201.2 2023). For these reasons, understanding both the mechanisms by which freezing pore water damages hardened cement paste—which is part of the concrete—and the conditions that must be satisfied before such damage can occur is a prerequisite to specifying, producing, and accepting freeze-thaw resistant concrete.

This section establishes the theoretical foundation upon which the remainder of this literature review is built. First, the principal theories proposed to explain the mechanisms causing freeze-thaw damage are reviewed, with emphasis on the hydraulic pressure theory and the osmotic pressure theory as presented in ACI 201.2 (2023). Second, the prerequisites for damage caused by cycles of freezing and thawing are examined; namely, that the temperature of the capillary pore water must reach or fall below its initial freezing temperature threshold and that the degree of saturation of the concrete must exceed a critical value (Powers 1949). The influence of pore size, water-to-cementing materials ratio (w/cm), curing duration, and air entrainment on these prerequisites is discussed.

2.1.1. Theories of the Mechanisms Causing Freeze-Thaw Damage

There is no consensus in the literature regarding the mechanisms responsible for freeze-thaw damage in hardened cement paste (ACI 201.2 2023). Freeze-thaw damage has been attributed to the buildup of hydraulic pressure as water is forced away from advancing freezing fronts, to osmotic pressure gradients driving water toward freezing sites, to vapor pressure potentials, and to combinations of these processes (ACI 201.2 2023). Although the proposed mechanisms differ in the driving force they identify, each theory predicts that damage results from pressures generated by the freezing of pore water and that these pressures can be relieved by closely spaced air voids. The two theories most widely cited in the literature, the hydraulic pressure theory and the osmotic pressure theory, are presented below, followed by the guidance provided in ACI 201.2 (2023) regarding their applicability.

2.1.1.1. Hydraulic Pressure Theory

The hydraulic pressure theory, first proposed by Powers (1949), attributes freeze-thaw damage to the pressure generated when freezing pore water expands. When the temperature reaches the initial freezing temperature threshold, ice crystals form first in the largest capillary pores. Because one cubic inch of water occupies approximately 1.09 cubic inches of space after freezing, the volume of ice plus unfrozen water exceeds the original capacity of the cavity, meaning that the pore must either dilate or expel the excess water (ACI 201.2 2023). The expelled water flows through the surrounding paste toward the nearest escape boundary—which in air-entrained concrete is an air void—and the resistance to this flow generates hydraulic pressure within the paste. The magnitude of this pressure increases approximately in proportion to the square of the distance from the void, with the pressure being zero at the void boundary (Powers and Helmuth 1956). If a point in the paste is sufficiently remote from an escape boundary, the pressure may be high enough to stress the surrounding paste beyond its tensile strength, thus causing permanent damage (Powers and Helmuth 1956). According to the hydraulic pressure theory (Powers 1949), freezing disrupts the paste only when the hydraulic pressure generated by freezing exceeds the tensile strength of the air-void-free shells of paste between the air voids. The practical implication of this theory is that disruptive hydraulic pressure can be prevented by reducing the distance between air voids to the point where the protected cement paste shells surrounding each void overlap (Powers and Helmuth 1956). This implication provides the theoretical basis for the spacing factor as an indicator of freeze-thaw durability, which is discussed later in this review.

2.1.1.2. Osmotic Pressure Theory

The osmotic pressure theory, developed by Powers and Helmuth (1956), was proposed after experimental observations could not be fully explained by hydraulic pressure alone. Under this theory, water in the largest voids freezes before water in the smaller voids, and when the water in the larger voids freezes, the concentration of dissolved salts in the remaining pore solution increases locally, causing a concentration gradient in the pore solution (ACI 201.2 2023). Water is thought to move from the smaller voids toward the larger ones to reduce this gradient, and the resulting flow is thought to cause damage (ACI 201.2 2023). A related thermodynamic argument applies to the gel water: if capillary water freezes, the gel water is no longer in thermodynamic equilibrium with the ice in the capillary pores since its free energy is higher than that of the ice. As a consequence, the gel water acquires an energy potential enabling it to move into the cavity, causing the ice crystal to grow and enlarge the cavity (ACI 201.2 2023). In contrast to the hydraulic pressure theory, in which water is expelled away from freezing sites, the osmotic pressure theory predicts that unfrozen water is drawn toward freezing sites.

2.1.1.3. Other Theories

Powers and Helmuth (1956) notes that experimental results showed significant evidence that water was diffusing from gel pores toward capillary pores and air voids, an observation consistent with the diffusion-driven flow predicted by the osmotic pressure theory. Because neither theory alone accounts for all experimental observations, a combined theory incorporating both hydraulic pressure and osmotic pressure gradients has been advanced (Pentalla 1998), and macroscopic ice lens growth has additionally been proposed to explain damage in concrete subjected to sustained freezing in the presence of an external water supply (Litvan 1978). Regardless of which mechanism predominately occurs under a given set of exposure conditions, all of the proposed mechanisms share a common premise: the pressures generated by freezing pore water are relieved when the paste contains a system of closely spaced air voids, and damage occurs only when sufficient freezable water is present in the paste (Powers 1949).

2.1.2. Prerequisites for Damage Caused by Cycles of Freezing and Thawing

For the mechanisms described in Section 2.1.1 to generate disruptive pressures, two prerequisites must be satisfied. First, the temperature of the pore water must fall below its initial freezing temperature threshold, which research in Section 2.1.2.1 will reveal is depressed below the normal freezing point of water by the size and shape of the pores in which the water resides. Second, the degree of saturation of the concrete must exceed a critical degree of saturation discussed in Section 2.1.2.2, below which the empty pore space within the concrete is sufficient to accommodate the volumetric expansion of the freezing water without generating disruptive pressure. Neither prerequisite is independently sufficient to cause damage (Powers 1949). Powers (1949) demonstrated that having a degree of saturation greater than the critical degree of saturation does not guarantee damage, as damage occurs only when the degree of saturation exceeds the critical value and the air voids are too widely spaced to relieve the resulting pressures. The initial freezing temperature threshold and the critical degree of saturation are examined in Sections 2.1.2.1 and 2.1.2.2, respectively.

2.1.2.1. Initial Freezing Temperature Threshold

Pore water in hardened cement paste does not freeze at the normal freezing point of bulk water. Experimental data show that a very small amount of water freezes near 32 °F, but in most specimens a significant amount of freezing occurs only after the temperature falls below the normal freezing point (Powers and Helmuth 1956). The explanation for this behavior lies in the geometry of the pore system: the capillary cavities are so small that the ice crystals they contain cannot exist except when the temperature is below the normal freezing point. The surface tension of the bodies of ice in capillary cavities puts them under a pressure that is higher the smaller the body; hence, the smaller the cavity, and of necessity the smaller the ice body, the higher the pressure and the lower the freezing point (Powers and Helmuth 1956).

The dependence of the freezing temperature on pore size has been quantified by several researchers. Jehng, Sprague, and Halperin (1996) measured the freezing behavior of cement paste with a w/cm of 0.43 and found that water in large capillary pores begins to freeze at approximately 28.1 °F, water in small capillary pores begins to freeze at approximately -9.7 °F, and gel pore water does not begin to freeze until approximately -63.7 °F. Wang et al. (2024) using nuclear magnetic resonance measurements on cement pastes with a w/cm = 0.45 cured for 25 days, observed rapid freezing of pore water in capillary pores ranging from 5 nanometers to 10 micrometers between 17.6 and 28.4 °F, with a reduced rate of freezing between -0.4 and 17.6 °F. Their results confirmed that the freezing temperature is related to the pore radius, with larger pores freezing first, followed by progressively smaller pores. Consistent with these findings, Powers (1949) reported that most of the capillary water in cement pastes cooled at 20 °F per hour freezes between 24.8 and 32 °F. Taken together, these studies indicate that the water most relevant to freeze-thaw damage, the capillary pore water, begins to freeze within a few degrees below 32 °F, whereas the gel pore water remains unfrozen at all temperatures encountered in service.

Supercooling of the pore water further complicates the identification of a single initial freezing temperature threshold. Kaufmann (2004) studied portland cement concretes with w/cm = 0.45, 0.50, and 0.63, with and without air entrainment, at ages of one to two years using ultrasonic pulse transit time measurements, in which pulse velocity increases significantly when pore water freezes. In cases in which the pore water was not supercooled, an increase in ultrasonic pulse velocity was observed at 32 °F, whereas in cases in which the pore water was supercooled, a rapid increase in pulse velocity occurred at approximately 24.8 to 26.6 °F. Their expansion measurements of the w/cm = 0.50 concrete suggested that freezing of capillary pore water initiates at 26.6 °F when supercooling occurs, and their acoustic emission test results for the w/cm = 0.63 concrete likewise showed that when supercooling occurs, freezing occurs at approximately 26.6 °F. The agreement among the three independent test methods indicates that supercooled pore water in concrete freezes at several degrees below the normal freezing point of 32 °F.

The initial freezing temperature threshold and the quantity of freezable water are influenced by the w/cm and curing history of the concrete. Banthia, Pigeon, and Lachance (1989) tested cement pastes with w/cm of 0.30, 0.36, and 0.50 cured for 1, 7, and 28 days and found that concrete mixtures with lower w/cm have lower initial freezing temperature thresholds and less ice formation than those with higher w/cm. Le Sage de Fontenay and Sellevold (1980) tested fully saturated cement pastes with w/c ranging from 0.4 to 0.7 and found that the lower the w/c, the lower the frozen water content. Banthia, Pigeon, and Lachance (1989) also found that longer curing periods of 7 and 28 days lead to less ice formation than a 1-day curing period, with there being a much larger difference in ice formation between the 1-day and 7-day cured pastes than between the 7-day and 28-day cured pastes. They therefore suggest that the majority of the pore refinement responsible for reducing the freezable water content occurs early in the curing process.

2.1.2.2. Critical Degree of Saturation

The second prerequisite for freeze-thaw damage is that the degree of saturation of the concrete must reach or exceed a critical value. The theoretical basis for the critical degree of saturation comes from the hydraulic pressure theory (Powers 1949)—because water expands by approximately 9% upon freezing, a paste whose pore space is less than approximately 91.7% filled with water contains sufficient empty volume to accommodate the expansion of the freezing water without generating disruptive pressure. Accordingly, Powers (1949) states that the intensity of the hydraulic pressure generated by freezing is heavily influenced by the degree of saturation near this threshold. Powers (1949) showed that when the degree of saturation is 99%, the hydraulic pressure generated is approximately 86% of what it would be at a degree of saturation of 100%, while at degrees of saturation of 98% and 97%, the generated pressures are approximately 68% and 56% of the fully saturated value, respectively. Therefore, it can be concluded that small changes in the degree of saturation of the paste produce large effects on the intensity of the hydraulic pressure generated by freezing.

Experimentally determined values of the critical degree of saturation fall slightly below the theoretical value of 91.7% proposed by Powers (1949). Li et al. (2012) tested mortar specimens simulating concrete with a w/cm of 0.42, cured at relative humidities of 50, 65, and 80% with paste air contents of 13, 22, and 31% (simulating total air contents of 4, 7, and 9% in concrete), and identified a critical degree of saturation in the 86 to 88% range, with no damage observed for specimens below 86% saturation. Notably, Li et al. (2012) found the critical degree of saturation to be independent of the air content of the specimens, although specimens with higher air contents absorbed more water overall because the air voids provide additional space for water, meaning that more water is needed to reach the critical degree of saturation in higher air content specimens. Obla, Kim, and Lobo (2016) likewise reported a critical degree of saturation for freeze-thaw failure of approximately 88% and observed that this value appears to be independent of the total air content, the type and content of supplementary cementing materials, and the w/cm. Moradllo et al. (2020) tested 30 concrete mixtures with w/cm = 0.40, 0.45, and 0.50 with total air contents in the 2.5 to 9.0% range and found that for mixtures without polycarboxylate-based high-range water-reducing (PC HRWR) admixture, the critical degree of saturation is 85%.

The consequences of exceeding the critical degree of saturation are largely independent of the total air content and the w/cm. Obla, Kim, and Lobo (2016) found that when the degree of saturation was greater than the critical degree of saturation, even air-entrained concrete with a total air content of 6.5% and w/cm = 0.45 failed AASHTO T 161 (2022) testing, and that specimens conditioned to a 100% degree of saturation failed freeze-thaw testing for all four mixtures evaluated. These included mixtures with w/cm = 0.45 and 0.65 with total air contents of 4.0 and 6.5%. Conversely, when the degree of saturation was lower than the critical degree of saturation, even concrete with a w/cm = 0.65 and 28-day compressive strength of approximately 4000 psi did not fail the freeze-thaw tests. For any given mixture, the lower the specimen's degree of saturation, the better its freeze-thaw performance and the greater its durability (Obla et al. 2016). These findings establish that the degree of saturation at the time of freezing, rather than the mixture proportions alone, governs whether the freezing event is damaging. This, however, does not suggest that air-entrainment is not essential to protecting concrete from freeze-thaw damage. Moradllo et al. (2020) found that at a given w/cm, the total air content is the most influential factor governing the degree of saturation of the cement paste, and that mixtures with higher total air contents require a longer time period to reach their critical degree of saturation than mixtures with lower total air contents. This extended time required for air-entrained mixtures to reach their critical degree of saturation leads to them having better freeze-thaw durability than non-air-entrained mixtures (Moradllo et al. 2020).

Because the critical degree of saturation itself is largely insensitive to mixture proportions, measures should be implemented to slow the rate at which concrete approaches the critical degree of saturation. Obla, Lim, and Lobo (2016) suggested that concrete mixtures with a low degree of saturation, low sorptivity, and high absorption capacity will require a longer time to attain the critical degree of saturation and will therefore perform better when exposed to cycles of freezing and thawing. Obla, Kim, and Lobo (2016) found that concrete mixtures with lower w/cm and those made with slag cement have lower a lower degree of saturation after curing and a lower measured sorptivity than those with higher w/cm and without slag cement. Additionally, Li et al. (2012) found that specimens cured at higher relative humidities absorbed less water and at a reduced rate than those cured at lower relative humidities, which was attributed to specimens cured at lower relative humidities having larger volumes of empty pores available to be filled during water sorption. The rate of moisture ingress, governed by the permeability and sorptivity of the concrete, thus determines the length of time a concrete element can be exposed to moisture before reaching the critical degree of saturation prerequisite for freeze-thaw damage. This relationship between permeability and freeze-thaw durability, along with the role of the air-void system in relieving the pressures generated once both prerequisites are satisfied, is further discussed in the following sections.

2.2 The Role of Air-Entrainment and Total Air Content in Freeze-Thaw Durability

The mechanisms and prerequisites of freeze-thaw damage reviewed in Section 2.1 indicate that entrained air protects concrete from damage caused by cycles of freezing and thawing through two distinct functions. First, closely spaced air voids serve as escape boundaries for the water expelled by advancing freezing fronts, relieving the hydraulic and osmotic pressures generated within the paste before those pressures exceed the tensile strength of the air-free webs of paste between the voids (Powers 1949; Powers and Helmuth 1956). Second, entrained air voids increase the time it takes for a concrete mixture to become critically saturated: Li et al. (2012) found that the degree of saturation decreases with increasing air content because the air voids provide additional space for water, meaning that more water must be absorbed before the critical degree of saturation is reached in higher air content specimens. Obla, Kim, and Lobo (2016) reported the same effect in concrete, observing that concrete mixtures with w/cm = 0.45 with higher entrained air contents have increased porosity and absorption capacity while also having lower degrees of saturation at the end of moist curing. Having a greater absorption capacity and a lower degree of saturation causes the time required to attain the critical degree of saturation to be extended. Because both the hydraulic and osmotic pressure relief and the extension of the time required for a concrete mixture to reach the critical degree of saturation depend on the presence of an adequate volume of entrained air, the total air content of a concrete mixture as measured by AASHTO T 152 (2024) or its ASTM counterpart ASTM C231 (2026), has historically served as the primary specification criterion for ensuring freeze-thaw durability. While total air content is the summation of both the entrapped and entrained air contents, it provides an accessible way to determine whether a mixture is likely to have an adequate level of freeze-thaw resistance before the placed concrete has hardened. This allows inadequate concrete delivered to the project to be rejected before it is placed and is essential for quality assurance. This section examines the role of air content in freeze-thaw durability by first comparing the performance of non-air-entrained and air-entrained concrete and then introducing the durability factor, the quantitative measure by which freeze-thaw resistance is assessed throughout the remainder of this review.

2.2.1. The Freeze-Thaw Resistance of Non-Air-Entrained versus Air-Entrained Concrete

The improvement in freeze-thaw durability provided by air entrainment exceeds that provided by any other concrete mixture proportioning decision. Cordon and Merrill (1963) concluded that the improvement of freeze-thaw durability due to air entrainment is of far greater magnitude than the improved durability experienced when the w/cm is decreased. The experimental evidence supporting this conclusion is extensive and consistent. Malhotra (1982) tested concrete mixtures with w/cm ranging from 0.35 to 0.70 and found that, regardless of the test procedure used, the test prisms cast from non-air-entrained concrete disintegrated at fewer than 31 cycles of freezing and thawing; the only exceptions were the prisms cast from the concrete with a w/cm of 0.35, which exhibited satisfactory resistance in AASHTO T 161 Procedure B with a durability factor greater than 90 after 300 cycles. Malhotra (1977) similarly reported that test prisms from a non-air-entrained control mixture with a w/cm of 0.65 disintegrated at fewer than 45 freeze-thaw cycles, whereas the prisms cast from air-entrained concrete mixtures performed well. Newlon (1978) likewise observed that non-air-entrained concrete specimens failed ASTM C666 testing when the test was conducted using both water and sodium chloride solution. Tanesi and Meininger (2006) reached the same conclusion for concrete mixtures with w/cm commonly used in highway construction, reporting that if no air entrainment is provided in concrete with a w/cm of 0.45, the freeze-thaw resistance of the concrete is poor.

The systematic comparison performed by Lomboy and Wang (2009) quantifies the disparity between non-air-entrained and air-entrained performance across a range of mixture proportions. Lomboy and Wang (2009) tested air-entrained and non-air-entrained concrete mixtures made with PC HRWR admixture at w/cm of 0.25, 0.35, 0.45, and 0.55, with the non-air-entrained mixtures limited to total air contents of 2.8% or less and the air-entrained mixtures containing a minimum of 6% total air content. All of the concrete mixtures without air-entraining admixture had a relative dynamic modulus of elasticity (RDME) of less than 40% of their original values at 300 freeze-thaw cycles, with a single exception discussed below. Additionally, at a given number of freeze-thaw cycles the RDME of the non-air-entrained mixtures decreased with increasing w/cm. Only the mixtures containing air-entraining admixture achieved spacing factors of 0.012 inches or less, thus suggesting that the non-air-entrained mixtures would not be freeze-thaw durable, an inference that the test results generally confirmed (Lomboy and Wang 2009). Contrasting this, all air-entrained concrete mixtures were freeze-thaw resistant, with each of them having an excellent durability factor of at least 85. The air-void systems of concrete mixtures measured by Pigeon, Gagne, Aitcin, and Banthia (1991) explain why non-air-entrained concrete lacks the ability to relieve freezing-induced pressures. In their four non-air-entrained mixtures, the specific surface varied between approximately 178 and 254 inches^{-1} and the spacing factor between 0.020 inches and 0.040 inches. These values are not close to meeting the recommended specific surface and spacing factor targets to ensure freeze-thaw durability of 600 inches^{-1} and 0.008 inches, respectively stated in ACI 201.2 (2023).

The exceptions to the poor performance of non-air-entrained concrete share a common characteristic: a very low w/cm that limits both the freezable water content and the rate of moisture ingress. The lone non-air-entrained mixture tested by Lomboy and Wang (2009) that survived freeze-thaw testing was made with Type IP cement (75% Type I cement and 25% Class F fly ash) at a w/cm of 0.25. It achieved a durability factor of 94.3 at 300 cycles and had a compressive strength of 12,760 psi, a rapid chloride penetration of 520 coulombs, and a porosity of 5%. Pigeon, Gagne, Aitcin, and Banthia (1991) observed a comparable exception in non-air-entrained concrete made with Type III cement and 6% silica fume at a w/cm of 0.30: after only one day of curing, a mixture with a spacing factor of 0.027 inches withstood more than 700 cycles without any deterioration, thus suggesting that for concrete mixtures with a w/cm = 0.30 containing silica fume, air entrainment may not be required to ensure adequate resistance to cycles of freezing and thawing. The protection afforded by a low w/cm was not universal, however, as Pigeon, Gagne, Aitcin, and Banthia (1991) found that other than the exception stated above, concrete mixtures made with Type I cement and 6% silica fume required air entrainment for good freeze-thaw resistance even at a w/cm of 0.30 after seven days of curing. These exceptions are consistent with the findings of Banthia, Pigeon, and Lachance (1989) and the guidance of ACI 201.2 (2023), in which lower w/cm reduce the freezable water content of the paste, and with the observation of Malhotra (1982) that of concrete mixtures made with w/cm = 0.35 to 0.70, the only non-air-entrained mixtures to resist disintegration were those with w/cm = 0.35. Because the research discussed in this section suggests that the survival of non-air-entrained concrete depends on mixture-specific combinations of cement type, supplementary cementing materials, and very low w/cm that cannot be reliably generalized, sufficient air entrainment remains the required means of ensuring freeze-thaw durability in practice.

Air-entrainment also affects the saturation behavior of concrete mixtures. Li et al. (2012) tested mortar specimens simulating concrete with a w/c of 0.42 and found that the specimens without air entrainment reached their critical degree of saturation much sooner than those with air entrainment, and that the use of air entrainment decreased the degree of saturation of the specimens at every stage of water absorption. Once the critical degree of saturation had been reached, however, the rate of damage was independent of the total air content (Li et al. 2012). For example, for a specimen with a 13% paste air content and a 96% degree of saturation, Li et al. (2012) recorded a dramatic increase in acoustic emission events when the temperature dropped below 17.6 °F, thus demonstrating that cement pastes with degrees of saturation greater than their critical degrees of saturation sustain internal damage during freezing regardless of the air voids available. Air entrainment therefore does not render concrete immune to frost damage. Rather, it extends the time required for the concrete to satisfy the critical degree of saturation prerequisite and, through the void spacing it provides, relieves the pressures generated when freezing does occur (Obla, Kim, and Lobo 2016; Powers 1949). Quantifying how effectively a given mixture performs these functions requires a standardized measure of freeze-thaw resistance, which is provided by the durability factor that is covered in more detail in the next subsection.

2.2.2. Durability Factor and its Relationship to Total Air Content

The durability factor is the quantitative measure of freeze-thaw resistance used throughout this review and is determined in accordance with AASHTO T 161 (2022) or its ASTM counterpart, ASTM C666 (2015). In these test methods, concrete prisms are subjected to cycles of freezing and thawing, and the relative dynamic modulus of elasticity (RDME) of each prism is measured at intervals throughout the test. The RDME is calculated by the following equation from AASHTO T 161 (2022):

$$P_c = \left(\frac{n_1^2}{n^2}\right) \times 100 \qquad \text{(Equation 2-2)}$$

where:

P_c = relative dynamic modulus of elasticity, after c cycles of freezing and thawing, (%),

n = fundamental transverse frequency at 0 cycles of freezing and thawing, and

n_1 = fundamental transverse frequency after c cycles of freezing and thawing.

After any prism's RDME fell below 60%, it was considered to have failed the freeze-thaw test. Its durability factor, DF, could then be calculated by the following equation given in AASHTO T 161 (2022):

$$DF = PN/M \qquad \text{(Equation 2-3)}$$

where:

DF = durability factor of the test specimen;

P = RDME at N cycles, (%);

N = number of cycles at which P reaches the specified minimum value for discontinuing the test or the specified number of cycles at which exposure is to be terminated, whichever is less; and

M = specified number of cycles at which the exposure is to be terminated.

As per AASHTO T 161 (2022), 300 cycles are used, hence $M = 300$. Once the durability factor for all three prisms had been determined, the average of the durability factors was calculated and reported.

Because internal microcracking caused by the pressures described in Section 2.1.1 reduces the RDME of the concrete, the durability factor provides a direct measure of the accumulated internal damage sustained by the specimen. Mass change measurements are also recorded during testing, and Tanesi and Meininger (2006) note that the mass change over cycles can be associated with concrete deterioration, with a mass gain indicating crack formation and water absorption through the cracks and a mass loss indicating significant scaling of the specimens during testing. Tanesi and Meininger (2006) found, however, that the mass loss did not present any trend in relation to the air-void system parameters, which supports the use of the durability factor rather than mass change as the primary measure of freeze-thaw resistance.

There is no universally accepted limit regarding what durability factor constitutes acceptable performance in AASHTO T 161 (2022). Freeman (2012) defined failure of ASTM C666 as having a durability factor less than 80, and Lomboy and Wang (2009) considered a durability factor of 85 at 300 cycles to be associated with adequate freeze-thaw resistance. Obla, Kim, and Lobo (2016) considered concrete mixtures with a durability factor greater than 80 after 300 cycles to have excellent performance under freeze-thaw exposure and considered specimens to have failed when the RDME dropped below 60% before 300 cycles were completed. Lower thresholds have been adopted on the basis of long-term field correlation; based on 17 years of experience in the use of ASTM C666 testing, the Virginia Highway and Transportation Council considers an acceptable durability factor at 300 cycles to be 60 (Newlon 1978), and Cordon and Merrill (1963) characterized concrete having a durability factor above 60 as exhibiting good durability and concrete having a durability factor below 40 as exhibiting poor durability. Consistent with the range of thresholds reported in the literature, concrete with a durability factor greater than or equal to 60 is considered in this study to have acceptable freeze-thaw resistance in Alabama, while concrete with a durability factor greater than or equal to 80 is considered to have excellent freeze-thaw resistance.

The relationship between total air content and the durability factor exhibits a transition from non-freeze-thaw-resistant to freeze-thaw-resistant behavior over a narrow range of air contents. Tanesi and Meininger (2006) tested concrete mixtures with w/cm of 0.40 to 0.50 and total air contents of 2.5 to 4.5% made with a natural air-entraining admixture, and found that mixtures with greater than 3.0% fresh air content performed well, achieving durability factors greater than 80 through more than 300 cycles of freezing and thawing. The mixtures with fresh air contents of 3.5% and 4.5% presented similar freeze-thaw resistance, lasting at least 300 cycles with durability factors higher than 80%, whereas the mixtures with air contents near 2.5% presented much lower freeze-thaw resistance (Tanesi and Meininger 2006). A correlation of 0.78 was also obtained between the fresh air content and the durability factor (Tanesi and Meininger 2006). Felice, Freeman, and Ley (2014) identified a comparable threshold, reporting that prisms tested per ASTM C666 achieved satisfactory performance with air contents near or above 3.5% in the concrete, or 11% in the paste, provided that the spacing factors were at or below 0.010 inches and the mixtures contained low dosages (3.7 fl. oz./cwt.) of lignosulfonate mid-range water-reducing admixture or none at all. For mixtures containing high dosages (10.2 fl. oz./cwt.) of lignosulfonate mid-range water-reducing admixture, Felice, Freeman, and Ley (2014) recommended a minimum air content of 4.0% in the concrete, or 13% in the paste. For satisfactory performance in moderate exposure conditions, Newlon (1978) recommends a minimum total air content of approximately 3.5%, and Janssen and Snyder (1994) observed that, within each fly ash replacement group they tested, durability generally decreased slightly with decreasing air content and increasing spacing factor. In concrete mixtures without polycarboxylate-based high-range water-reducing (PC HRWR) admixture, it is clear that the presence of a high volume of entrained air significantly benefits the air-void system. Zia et al. (1993) reported that all of the high-performance concrete mixtures containing roughly 5% entrained air exhibited greatly enhanced freeze-thaw durability, with durability factors of at least 80 as measured by ASTM C666 Procedure A with the only exceptions being the mixtures made with washed rounded gravel whose coarse aggregate lacked resistance to freezing and thawing.

The severity of AASHTO T 161 (2022) relative to field exposure conditions must be considered when interpreting durability factors. Temperature data collected by Nooken, Hooton, and Rogers (2004) from slabs and beams exposed to cycles of freezing and thawing over a four-year period in Kingston, Ontario revealed that temperatures both inside and outside the concrete rarely reached the 0 °F attained in AASHTO T 161, that the median durations of the freezing portion of the field freeze-thaw cycles were far longer than in the test, with a median freezing cycle length of 16 hours for concrete 2 inches from the surface at a freezing temperature of 28 °F compared to the two to five-hour freezing cycle of AASHTO T 161 (2022), and that the median freezing rate in the slabs and beams did not exceed 1.8 °F per hour, whereas the freezing rate in AASHTO T 161 (2022) is 10.7 to 26.7 °F per hour. The direction in which these differences bias the severity of AASHTO T 161 (2022) is not uniform. Powers (1949) found that the severity of the freeze-thaw test increases with increases in the cooling rate, indicating that the rapid cooling of AASHTO T 161 is conservative relative to field cooling rates. Conversely, Stark (1989) subjected concretes with different entrained air-void systems to long and short cycles of freezing and thawing in a 4% sodium chloride solution and found that the long freeze-thaw cycles were more severe than the short cycles for the same number of cycles, even where the air-void spacing factors were no greater than 0.008 inches, a finding consistent with the ice accretion theory of frost damage. The influence of specimen curing on the test result is limited; Janssen and Snyder (1994) observed very little difference in durability between specimens cured for 14 days and those cured for 28 days, indicating that most of the factors that influence durability, including the air-void system, the water pore system, and the strength, are well established after an age of 14 days.

The transition in the durability factor over the 2.5 to 4.5% total air content range establishes total air content as a meaningful, but incomplete, predictor of freeze-thaw resistance. Ley et al. (2017) found that a 2.75% air volume was sufficient to produce a durability factor above 70 for a concrete mixture containing only a natural (wood rosin) air-entraining admixture, whereas 6% total air content was needed to achieve the same performance for the companion mixture containing the same air-entraining admixture and a PC HRWR admixture, and they therefore concluded that total air content alone is not a reliable predictor of durability. Freeman (2012) documented the same limitation. A mixture containing only wood rosin air-entraining admixture had a spacing factor close to 0.008 inches with only 3.5% total air content and achieved an average durability factor of 97, while a mixture containing PC HRWR admixture had a higher total air content of 5.3% but a larger spacing factor of 0.013 inches failed ASTM C666 testing in just 137 cycles. Powers (1949) states the underlying principle directly: the total air content required is that which causes the air-void system to have a sufficiently small spacing factor, and the total air content required for a given rate of cooling depends on the paste content, the specific surface of the voids, and the maximum permissible spacing factor. The total air content therefore serves as an easily testable indicator for the characteristics of the air-void system that actually governs freeze-thaw resistance, and the reliability of the total air content as an indicator depends on the admixtures used in the mixture. Other indicators that characterize the air-void system, including the spacing factor, the specific surface, and the SAM number, and their relative capacities to predict the durability factor, are the subject of the following section.

2.3 Indicators of Freeze-Thaw Durability

The finding presented in Section 2.2 that the total air content is an easily testable but incomplete predictor of the durability factor motivates an examination of the full set of indicators available to predict the freeze-thaw durability of concrete. These indicators divide into two categories according to when they can be measured. The total air content, measured on freshly mixed concrete by the pressure method of AASHTO T 152 (2024), and the SAM number, measured on freshly mixed concrete by the sequential pressure method of AASHTO T

395 (2024), are available at the time of placement and can therefore support acceptance decisions before concrete placement. The spacing factor and the specific surface, determined by the microscopical examination of hardened concrete in accordance with ASTM C457 (2024), characterize the air-void system directly but cannot be obtained until after the concrete has hardened, by which time a deficient element can no longer be rejected without removal. The value of each indicator is therefore judged by two criteria: the strength of its relationship to the durability factor determined in accordance with AASHTO T 161 (2022), and the concrete state when it can be measured. This section evaluates the total air content, the SAM number, the spacing factor, and the specific surface against these criteria and closes by examining the differences between the fresh and hardened total air contents on which the reliability of fresh-concrete acceptance testing depends.

2.3.1. Total Air Content

The total air content is the most widely specified indicator of freeze-thaw durability because it is inexpensive to measure, familiar to concrete technicians, and can be performed on fresh concrete before placement. The evidence reviewed in Section 2.2 establishes a relationship between the total air content and the durability factor. Tanesi and Meininger (2006) obtained a correlation of 0.78 between the fresh air content and the durability factor for concrete with w/cm of 0.40 to 0.50 made with a vinsol resin air-entraining admixture, with mixtures above 3.0% fresh air content achieving durability factors greater than 80 through more than 300 cycles. The thresholds identified across studies are likewise consistent, with satisfactory performance reported near or above 3.5% total air content by Felice, Freeman, and Ley (2014) and Newlon (1978), and Sutter (2007) reporting that adequate spacing factors are achievable with 3.0 to 4.0% total air by volume, depending upon the air-entraining admixture used.

The stipulation by Sutter (2007) that the total air content required to achieve an adequate spacing factor depends on the air-entraining admixture used identifies the limitation of the total air content as an indicator. Ley et al. (2017) found that, at similar total air contents, it is possible for two concrete mixtures to have very different spacing factors: one of their mixtures containing only a wood rosin air-entraining admixture required 4.5% total air content to obtain a spacing factor of 0.008 inches or less, while the same mixture containing the same air-entraining admixture and a PC HRWR admixture required 7.5% total air content to obtain the same spacing factor. Based off this, they concluded that the total air content alone does not always provide an indication of the quality of the air-void system (Ley et al. 2017). The inconsistency of capability of the total air content to provide an indication of the durability factor, as was also discussed previously in Section 2.2.2 was also demonstrated by Freeman (2012). The reason for this inconsistency in the total air content's ability to predict the durability factor is that the total air content measures the volume of air in the concrete without regard to how that volume is distributed among voids of different sizes. Ley et al. (2017) reason that because the distribution, rather than the volume, governs the air-void spacing that relieves freezing-induced pressures, an indicator sensitive to the void size distribution is required when admixtures that negatively affect the air-void system are used.

2.3.2. SAM Number

The Super Air Meter (SAM), also known as the Sequential Pressure Meter, was developed to provide an indicator of the air-void size distribution that, unlike the spacing factor, can be measured on fresh concrete (Ley and Tabb 2014). The test, standardized as the sequential pressure method in AASHTO T 395, uses an altered version of the conventional pressure meter. The bottom chamber of the meter is filled with fresh concrete in three layers that are rodded 25 times each, the top chamber is clamped on and filled with water, and the top chamber pressure is sequentially increased to 14.5, 30, and 45 psi, before it is allowed to equilibrate with the bottom chamber pressure. After the pressurization to 45 psi step is completed, the pressure is then released, the pressurization sequence repeated, and the SAM number is calculated as the difference between the equilibrium pressures at the top chamber pressure step of 45 psi across the two pressurization cycles (Ley et al. 2017). Although a pressure difference, the SAM number is reported without units. The SAM meter measures the total air content concurrently, and according to Ley and Tabb (2014), a very strong correlation exists between the total air content determined by ASTM C231 and by the SAM test, with only a 5.5% difference and an r-squared value of 0.98 across the 53 samples compared.

According to data from Ley et al. (2017), the SAM number correlates with the spacing factor more strongly than the total air content. Ley et al. (2017) found that lower SAM numbers generally indicate lower spacing factors, and for the 303 laboratory and field specimens they tested, there was a high correlation between a low SAM number and a low spacing factor. A SAM number of 0.20 identified whether the spacing factor was above or below 0.008 inches for 88% of their data, and a SAM number of 0.25 identified whether the spacing factor was greater or less than 0.010 inches for 85% of the data (Ley et al. 2017). According to Ley et al. (2017), the SAM number predicts the durability factor with similar accuracy. Ley et al. (2017) found that the durability factor versus SAM number curves for two different concrete mixtures largely overlapped, with lower SAM numbers suggesting higher durability, and a SAM number of 0.32 showing nearly 90% correct prediction capacity for durability factors of 60 and 70 and approximately 87% correct prediction capacity for a durability factor of 80. In the previous sentence, the term "correct prediction capacity" refers to the rate at which the SAM number correctly determines whether a concrete mixture will have a durability factor less than or greater than a specific value such as 60. Among the SAM test of AASHTO T 395, the hardened air-void test of ASTM C457, and the rapid freeze-thaw test of ASTM C666 Procedure B, the SAM had the lowest coefficient of variation (Ley et al. 2017). The coefficients of variation for AASHTO T 395, ASTM C457, and ASTM C666 were 15.2, 20.1, and 22.7%, respectively (Ley et al. 2017).

The superiority of the SAM number over the fresh total air content is not supported by every investigation. Tanesi et al. (2016) reported a better correlation between the total air content and the spacing factor than between the SAM number and the spacing factor. Additionally, Tanesi et al. (2016) found no significant difference between the total air content and the SAM number in their ability to identify potentially freeze-thaw susceptible mixtures, since the number of false positive and false negative cases was similar for both indicators. The same investigation documented mixtures with SAM numbers much higher than 0.20 psi and spacing factors of 0.010 inches or higher that still performed well under ASTM C666 (Tanesi et al. 2016), thus indicating that a failing SAM number, like a failing spacing factor, does not guarantee poor freeze-thaw performance. Some current national guidance nonetheless incorporates the SAM number as an alternative acceptance path. AASHTO R 101-25 (2025) recommends a total air content of four percent or greater together with a SAM number that is less than or equal to 0.20 determined according to AASHTO T 395, or a total air content ranging from five to eight percent determined according to AASHTO T 152. The structure of this recommendation reflects the evidence reviewed above: when the air-void size distribution is verified by the SAM number, a lower total air content is accepted, whereas in the absence of that verification, a higher total air content may be required to provide confidence that an adequate air-void system has been achieved.

2.3.3. Spacing Factor, Specific Surface, and the Air-Void System

The spacing factor and the specific surface are the parameters of the hardened air-void system against which the fresh-concrete indicators of Sections 2.3.1 and 2.3.2 are compared, and both derive directly from the hydraulic pressure theory presented in Section 2.1.1.1. The spacing factor is a measure of the average distance from the middle of a point in cement paste to the nearest air-void (ACI 201.2 2023), thus representing the average maximum distance water would have to travel to reach a void (Powers 1949). Because the hydraulic pressure generated by freezing increases approximately in proportion to the square of the distance from the nearest escape boundary, the theory derived by Powers (1949) requires that the average distance from void to void through the paste should not exceed approximately 0.020 inches, meaning that the maximum distance from a point in the paste to the nearest void is about 0.010 inches or less. Powers (1949), based off experimental results also states that the actual maximum spacing factor estimated for certain frost-resistant concretes was about 0.010 inches, a result considered to be in excellent agreement with the theoretical calculations. The physical significance of the spacing factor limit is supported by direct expansion measurements taken by Powers and Helmuth (1956) who found that in cement pastes cooled to -4 °F, the expansion and deterioration of the cement paste caused by freezing decreases as the spacing factor decreases.

The specific surface is a measure of the surface area per unit volume of voids (Powers 1949). Under the basic assumption that all voids are spherical, the specific surface is a function of the average chord length alone and is therefore a good indicator of the average void size (Powers 1949). The generally accepted limits for concrete with good resistance to freezing and thawing are a maximum spacing factor of approximately 0.008 inches and a minimum specific surface of 600 $in.^2/in.^3$ (ACI 201.2 2023). Supporting recommendations for a system of closely spaced, small air voids is a Federal Highway Administration (FHWA) report (1989) that recommends that the air voids be small to provide sufficient freeze-thaw resistance, with diameters in the range of 0.002 to 0.05 inches, to ensure that the required spacing factor is obtained even at low total air contents.

There is also a relationship between the size distribution of the air voids and the spacing factor. Lomboy and Wang (2009) found that the spacing factor decreased as the volume of small air voids finer than 0.012 inches measured by air-void analyzer increased with a correlation coefficient (R^2) of 0.96, whereas the relationship between the total air content and spacing factor yielded an R^2 of only 0.83. According to Lomboy and Wang (2009), this demonstrates that the spacing factor is governed more by the small-air-void fraction rather than by the total air volume. Freeman (2012) reached the same conclusion by counting voids directly: all concrete mixtures with more than 6 voids per inch smaller than 0.008 inches had durability factors greater than 80, with a single exception having a durability factor of 69. Furthermore, no specimen with fewer than 5 voids per inch smaller than 0.008 inches passed ASTM C666 testing. For the mixtures examined in that study, a spacing factor of 0.0094 inches, a minimum specific surface of 600 $in.^2/in.^3$, and a minimum of 6 voids per inch smaller than 0.008 inches were required to achieve adequate freeze-thaw resistance (Freeman 2012).

The exact air-void system parameters required to ensure adequate freeze-thaw durability are also influenced by the admixtures used. Felice, Freeman, and Ley (2014) found that all mixtures containing only an air-entraining admixture, or a low dosage of lignosulfonate mid-range water-reducing admixture with a natural (wood rosin) air-entraining admixture, were durable when the spacing factor was equal to or less than 0.010 inches. However, mixtures containing a high dosage of lignosulfonate mid-range water-reducing admixture required spacing factors of 0.008 inches or less, the ACI 201.2 (2023) recommended limit (Felice, Freeman, and Ley 2014). Based on those findings, Felice, Freeman, and Ley (2014) recommended that a spacing factor of 0.008 inches remain the suggested maximum for a mixture to ensure freeze-thaw durability regardless of the admixtures used.

The spacing factor limit can also be conservative for some concrete mixtures. Attiogbe (1992) noted that properly air-entrained concrete mixtures containing sulfonated melamine formaldehyde condensate and modified lignosulfonate HRWR admixtures can have adequate freeze-thaw resistance at spacing factors greater than the ACI 201.2 (2023) recommended maximum of 0.008 inches. The concrete mixtures investigated in that study had spacing factors ranging from 0.010 to 0.017 inches, and in spite of the increased air-void spacing, the freeze-thaw durability of the concrete mixtures was adequate (Attiogbe 1992).

Other instances of concrete mixtures having spacing factors greater than 0.008 inches but still having adequate durability have been reported. Malhotra (1977) reported that air-entrained concrete with a spacing factor of 0.010 inches likewise performed satisfactorily in freeze-thaw testing. Additionally, Tanesi et al. (2016) found that some mixtures performed well under ASTM C666 testing despite them having spacing factors of 0.010 inches or higher. These observations suggest that the 0.008 inch limit is a sufficient but overly conservative condition for freeze-thaw resistance, with the degree of conservatism depending on the admixture used. The hardened spacing factor and specific surface remain the most direct indicators of the air-void system, but because they are determined by the microscopical examination of hardened concrete in accordance with ASTM C457 (2024), they cannot support acceptance decisions at the time of placement.

2.3.4. Differences between the Fresh Total Air Content and the Hardened Total Air Content

The total air contents reported by tests performed on fresh concrete (AASHTO T 152 or ASTM C231) and those performed on hardened concrete (ASTM C457) are not always the same. This is important because field acceptance of concrete that will be exposed to cycles of freezing and thawing is based on the total air content of fresh concrete, which may be different from the total air content in the hardened concrete that will actually help to resist in-place cycles of freezing and thawing.

The reported differences are modest in magnitude but inconsistent in direction. Tanesi and Meininger (2006) found that the fresh total air content measured according to ASTM C231 was always lower than the hardened total air content measured according to ASTM C457 and, in most cases, lower than the modified point count total air content measured according to ASTM C457 as well. Sutter (2007) similarly observed that fresh concrete tests for total air content seem to underestimate the hardened total air content, which he suggested may be related to the nature of the air-void size distribution produced by a synthetic air-entraining admixture. Lomboy and Wang (2009) reported the opposite direction of disagreement, with the hardened total air content measured by ASTM C457 being slightly lower than the fresh total air content measured by ASTM C231. Felice, Freeman, and Ley (2014) quantified the magnitude of the discrepancy, reporting that in mixtures without lignosulfonate mid-range water-reducing admixture, the average difference between the ASTM C231 and ASTM C457 concrete air contents was 0.47% with a standard deviation of 0.40%, and in mixtures with lignosulfonate mid-range water-reducing admixture, the average absolute difference was 0.57% with a standard deviation of 0.35%. They did not however, report whether the fresh total air content measured by ASTM C231 or the hardened total air content measured by ASTM C457 was greater on average.

2.4 Other Factors Affecting Freeze-Thaw Durability

The preceding sections established that the air-void system governs freeze-thaw durability and that the indicators available to characterize that system differ in predictive capacity and whether they can be measured in the fresh or hardened concrete state. This section individually examines other factors that potentially affect freeze-thaw durability including the type of air-entraining admixture, inclusion of polycarboxylate-based high-range water-reducing (PC HRWR) admixture, w/cm, permeability, strength of the concrete, and use of supplementary cementing materials (SCMs).

2.4.1. Type of Air-Entraining Admixture

Air-entraining admixtures are defined as “admixtures that cause the development of a system of microscopic air bubbles in concrete, mortar, or cement paste during mixing, usually to increase its workability and resistance to freezing and thawing” (ACI CT 2025). Air-entraining admixtures are surface-active chemicals, also known as surfactants, and consist of long-chain organic molecules, one end of which is hydrophilic while the other end is hydrophobic (Mehta and Monteiro 2014). Generally, surfactants used as air-entraining admixtures consist of salts of wood resins (natural air-entraining admixtures), proteinaceous materials and petroleum acids, and synthetic detergents (Mehta and Monteiro 2014). They concentrate at the air-water and cement-water interfaces and lower the surface tension, promote bubble formation, and counteract the tendency for the dispersed bubbles to coalesce (Lea 1971). The hydrophilic end of the chain is also polar, which allows it to become bound to cement particles which helps to stabilize the bubbles (Lea 1971). Figure 2-1 shows the interactions between air-entraining admixture (labelled as “surfactant molecule”), air bubbles, and cement particles for better visualization.

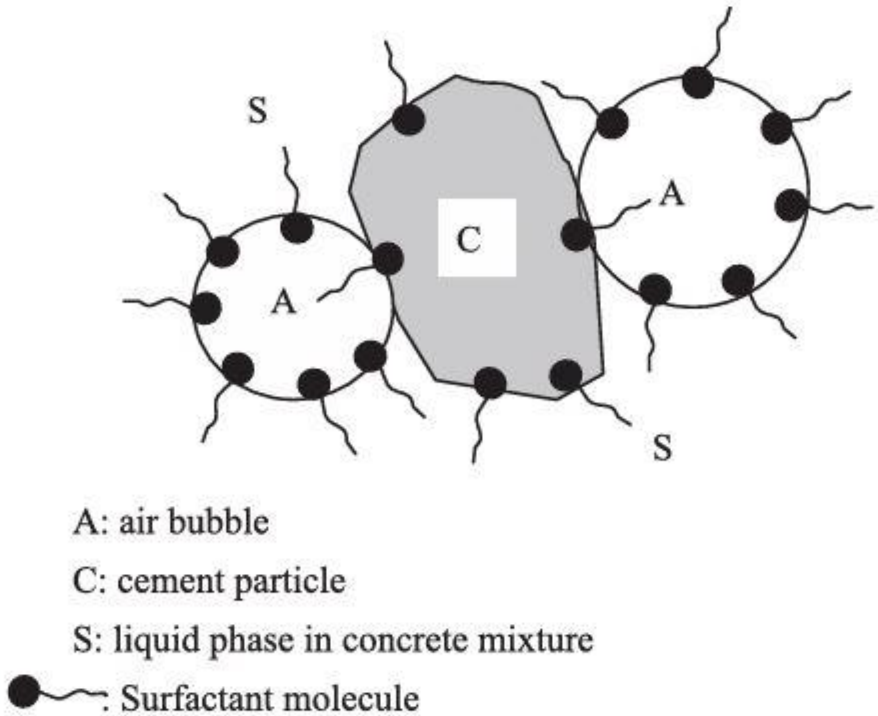


Figure 2-1. Mechanism of Air-Entraining Admixtures (Du and Folliard 2005).

Xiang et al. (2022) describe the bubble life cycle in terms of four stages: generation, growth, stability, and rupture, with bubble growth occurring when gas diffuses through the bubble film under the pressure gradient between bubbles. Because small bubbles have a high internal gas pressure and large bubbles a low internal gas pressure, small bubbles macroscopically converge toward large bubbles and gradually shrink until they disappear, while large bubbles gradually grow until they burst. The stability of the bubbles is affected by many factors, including the strength of the bubble liquid film and the diffusion rate of gas through the film (Xiang et al. 2022). The air-void system measured in the hardened concrete is therefore the equilibrium point of a competition between stabilization and coarsening processes, and the chemistry of the air-entraining admixture used influences the total air content.

The earliest work on freeze-thaw resistance, as well as the recommendations for air-void systems reviewed in Section 2.3, were based on research on concretes containing natural (vinsol resin) air-entraining admixtures, and the scarcity of vinsol resin admixture is responsible for the increasing use of synthetic admixtures (Tanesi and Meininger 2006). However, given the increasing usage of synthetic air-entraining admixtures, it is important to evaluate the performance of synthetic air-entraining admixtures compared to that of natural air-entraining admixtures. Freeman (2012) compared the stability of concrete air-void systems over time made with vinsol resin, wood rosin, and synthetic air-entraining admixtures and found that the synthetic air-entraining admixture produced concrete with the lowest spacing factor and the highest specific surface, exhibited the smallest changes in the air-void system from 0 to 60 minutes, and produced the most stable air-void system despite having the smallest air-entraining admixture dosage by a significant margin. The vinsol resin concrete mixture showed the most dramatic change, with its spacing factor nearly doubling between 0 and 60 minutes and its specific surface reduced by almost 38%, while the wood rosin mixture lost air content without much change in spacing factor and with a specific surface that actually increased over time (Freeman 2012). Counterintuitively, the type of air-entraining admixture did not, however, seem to impact the total air loss over time in concrete (Freeman 2012).

There is evidence to suggest that the relationship between air-void system quality and freeze-thaw performance is not similary preserved across air-entraining admixture types. Tanesi and Meininger (2006) found that for the mixtures prepared in their study and the specific admixtures used, the vinsol resin mixtures exhibited better freeze-thaw resistance than the synthetic air-entraining admixture mixtures although they had a worse air-void system, with higher spacing factors and lower specific surface. Tanesi and Meininger (2006) note that this was an unexpected observation for which the reasons are not known and which they state cannot be generalized for all air-entraining admixtures without further research. Despite these variations in the air-void systems of concrete mixtures made with different kinds of air-entraining admixtures, Felice, Freeman, and Ley (2014) found that the total air content needed to ensure freeze-thaw durability is independent of air-entraining admixture type, as their evaluated concrete mixtures had satisfactory resistance to cycles of freezing and thawing when tested per ASTM C666 if they had at least 3.5% total air content in the concrete, or 11% total air content in the paste, regardless of whether the concrete was made with vinsol resin, wood rosin, or synthetic air-entraining admixture.

2.4.2. Inclusion of Polycarboxylate-Based High-Range Water-Reducing (PC HRWR) Admixture

The use of some polycarboxylate-based high-range water-reducing (PC HRWR) admixtures may also affect the air-void system and therefore the durability factor. PC HRWR admixtures are the third generation of high-range water-reducing admixtures (HRWR) after the previous two generations, which were sulfonated salts of melamine and naphthalene formaldehyde condensates (Mehta and Monteiro 2014). HRWR admixtures are defined as being "water-reducing admixtures that are capable of producing large water reduction or great flowability without causing undue set retardation or entrainment of air in mortar or concrete" (ACI CT 2025). Like air-entraining admixtures, water-reducing admixtures are also surfactants and are usually composed of salts and modifications, derivatives of lignosulfonic acid, hydroxylated carboxylic acids, and polysaccharides or any combination of those (Mehta and Monteiro 2014).

PC HRWR admixture is a comb-like structure consisting of an anionic backbone and long polyethylene oxide side chain with a hydroxyl or methyl group at its end (Ma et al. 2022). The two primary methods by which the PC HRWR admixture increases flowability of concrete mixtures are by electrostatic repulsion and steric hindrance (Ma et al. 2022) which cause cement grains to be well dispersed and thus prevent them from flocculating. PC HRWR admixtures exhibit a linear water-reduction response with increasing dosage and do not delay the set and strength gain of concrete mixtures at recommended dosage rates (Freeman 2012), properties that have made them ideal constituents of modern low w/cm concretes.

Despite the benefits listed above, the use of PC HRWR admixture may negatively influence the air-void system (Freeman 2012). Freeman (2012) found that, at a given total air content, a mixture containing PC HRWR admixture will have a larger spacing factor than a mixture without PC HRWR admixture, and that in order to achieve a given spacing factor, a higher volume of air is needed in a mixture containing PC HRWR admixture to obtain adequate freeze-thaw resistance. From this, Freeman (2012) concluded that the inclusion of PC HRWR admixture coarsens the air-void system. The coarsening impacts the air-entraining admixture dosage as well as the air-void distribution. At comparable total air contents, the dosage of air-entraining admixture used in the mixtures containing PC HRWR admixture (0.27 oz./cwt) was generally much lower than in mixtures containing only wood rosin without PC HRWR admixture (0.67 oz./cwt.). This implies either an interaction between the PC HRWR admixture and the air-entraining admixture or that the PC HRWR admixture is entraining some air. The resulting reduction in dosage likely means that less of the air-entraining admixture is present at the surfaces of the voids, which may change the stabilized void distribution (Freeman 2012).

The PC HRWR admixture may also destabilize the air-void system over time. In a study by Freeman (2012), combinations of three air-entraining admixtures and five PC HRWR admixtures were tested over the course of two hours to determine their impact on the air-entrainment of concrete mixtures and the stability of air-void systems over time. In the concrete tested by Freeman (2012), the mixtures containing PC HRWR admixtures lost more air than the mixtures containing only wood rosin air-entraining admixture. In concrete consolidated and tested at 60 minutes, the average loss in total air content was 45% relative to its initial value for mixtures containing PC HRWR admixture and 32% for mixtures without it. In concrete consolidated after 2 hours, the average loss of total air content was 50% for mixtures containing PC HRWR admixture and 31% for mixtures without PC HRWR admixture. While the presence of the PC HRWR admixture affected the air loss, the choice of the specific PC HRWR admixture did not have an observable impact on air loss, as all of the different PC HRWR admixtures performed similarly (Freeman 2012).

The proposed mechanism by which instability of the air-void system stems from the dispersing function of the admixture. Because there is a strong adhesion between cement grains and the surfaces of entrained air voids, and PC HRWR admixtures repel cement grains through steric and electrostatic hindrance, it is possible that this repulsion interferes with the adhesion of the air-void surfaces to the cement grains, thus reducing the stability of the voids by allowing them to escape to free surfaces at the top of the concrete or within larger voids (Freeman 2012). Consistent with this mechanism, the act of consolidation reduces the air loss: for mixtures containing only wood rosin, the average loss of air after 2 hours decreased from 31% to 5% when the concrete was consolidated initially, and for mixtures containing PC HRWR admixture, the average loss changed from 50% to around 10%, therefore suggesting that the physical rearranging of materials due to consolidation compensates for the loss in attraction between the voids and the cement grains (Freeman 2012). The results labelled "Modified C231" in Figure 2-2 show this phenomenon for the wood rosin and PC HRWR admixture concrete mixtures.

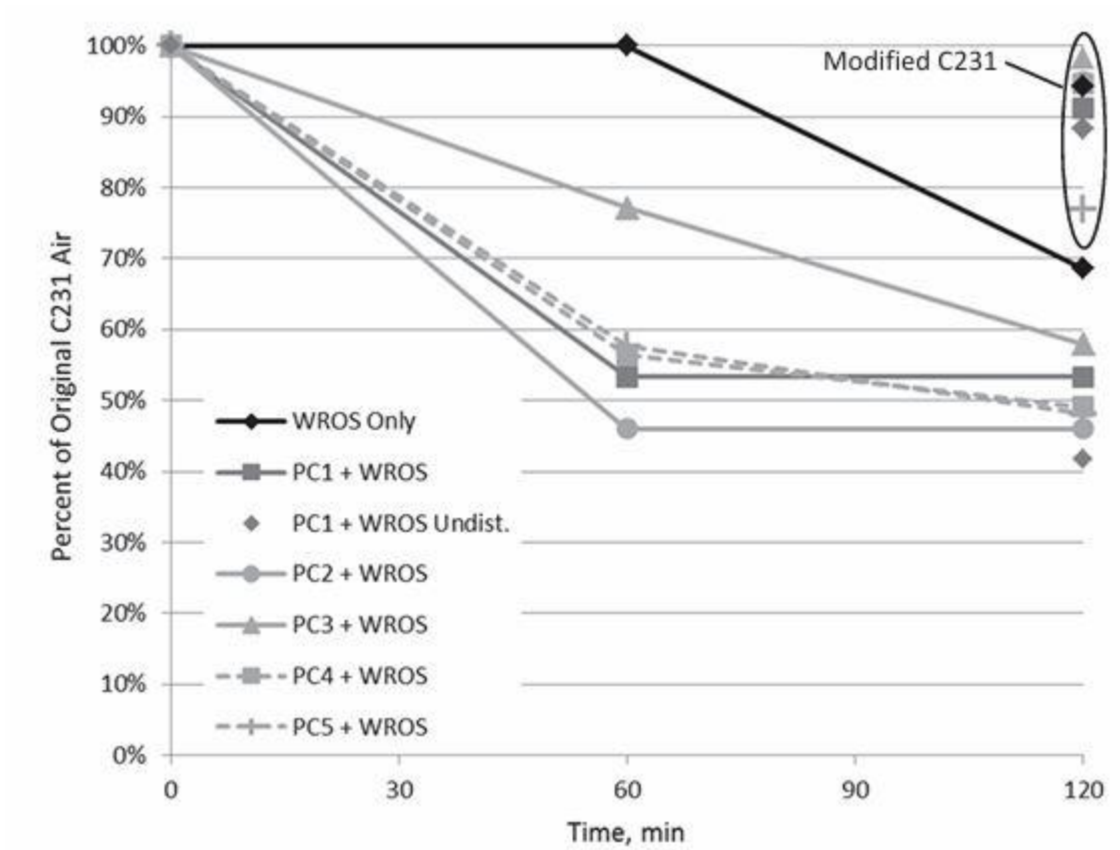


Figure 2-2. The changes in total air content over time of select concrete mixtures. (Freeman 2012).

In addition to the stability of the air-void system, the use of PC HRWR admixtures may also impact the quality of the air-void system. In Freeman's (2012) study, all of the air-void systems of the concrete mixtures made with five different PC HRWR admixtures plus wood rosin air-entraining admixture exhibited similar losses in total air content changes over two hours, implying that the stability of the air-void system is likely based on the air-entraining admixture used, while the quality of the air-void system is likely controlled more by the chosen PC HRWR admixture (Freeman 2012). These loses in total air content over the course of two hours are shown in Figure 2-2. For a given air-entraining admixture, the choice of the PC HRWR admixture affects the overall quality of the air-void system over time, and for a given PC HRWR admixture, the choice of air-entraining admixture affects the stability of the system (Freeman 2012). The consequences for freeze-thaw testing were direct: three of five concrete mixtures containing PC HRWR admixture, wood-rosin air-entraining admixture, and 4.5 to 5.7% total air contents, which is normally enough to expect satisfactory performance, surprisingly failed ASTM C666 (Freeman 2012). The two mixtures that passed ASTM C666 testing had hardened air-void systems within the recommended parameters. These differences in performance are likely dependent on the specific chemical composition of each PC HRWR admixture (Freeman 2012).

Furthermore, according to Freeman (2012), the negative effects associated with using PC HRWR admixture can be partially mitigated by either reducing the w/cm or reducing the dosage of PC HRWR admixture, which improves the quality of the air-void system and therefore the durability factor. The structural chemistry underlying the differences in performance of different PC HRWR admixtures has been examined at the air void scale. The acid-to-ether ratio, sulfonic acid group, ester group, and type of air-entraining agent used with the polycarboxylate structure have a significant impact on the air voids (Xiang et al. 2022). Moreover, the bubbles introduced by the PC HRWR admixture itself are normally irregular and unstable, thus making them more likely to coalesce during vibration and transportation (Xiang et al. 2022). Computed tomography three-dimensional reconstruction of fresh mortar has directly confirmed the coalescence of adjacent bubbles, with long side-chain polycarboxylate producing a decrease in small bubbles, an increase in large bubbles, and earlier bubble coalescence and rupture time (Jiang et al. 2021). The proposed explanation is that the greater relative molecular mass of the long side-chain polycarboxylate makes it less likely to be retained in the free solution of the fresh concrete, increasing the surface tension and thinning the bubble liquid film (S. C. Xiang et al. 2015).

2.4.3. Water-to-Cementing Materials Ratio

The w/cm potentially impacts freeze-thaw durability through its impact on various concrete properties such as pore structure, freezable water content, initial freezing temperature threshold, and degree of saturation. The capillary cavities are more numerous and larger the higher the w/cm and the shorter the period of curing (Powers and Helmuth 1956). Limiting the w/cm to a specified maximum has the effect of reducing the amount of freezable water initially in the cured concrete (ACI 201.2 2023). Consistent with the finding of Banthia, Pigeon, and Lachance (1989), presented in Section 2.2.1, the lower w/cm lead to lower initial freezing temperature thresholds and less ice formation. A lower w/cm also impacts the time it takes for concrete mixtures to reach their critical degree of saturation. This is evident in the results of Obla, Kim, and Lobo (2016) that show that mixtures with a lower w/cm have a lower degree of saturation after moist curing, lower sorptivity, and are therefore expected to require a longer time to attain the critical degree of saturation.

Tanesi and Meininger (2006) found that, within the 0.40 to 0.50 range tested, the w/cm does not appear to play a significant role in the freeze-thaw resistance, with a correlation between the w/cm and the durability factor of only 0.04. Moreover, their results show that reducing the w/cm does not significantly affect freeze-thaw resistance for air-entrained concrete mixtures with 3.5 and 4.5% total air content, while reducing the w/cm slightly improves freeze-thaw resistance for concrete mixtures with 2.5% total air content (Tanesi and Meininger 2006). Felice, Freeman, and Ley (2014) likewise found no difference in the minimum total air content required for satisfactory ASTM C666 performance across the w/cm investigated, with mixtures at w/cm of 0.41 and 0.45 exhibiting similar performance and similar air-void system quality. They noted that although the influence of the w/cm on tensile strength and porosity would lead one to expect that a lower quality air-void system may be acceptable at lower w/cm, the phenomenon may only be observable if more mixtures with air contents between 2.5 and 3.5% are investigated. Lomboy and Wang (2009) found that for concrete mixtures with air-entraining admixture, the relationship between the durability factor and the w/cm was not clear, although the relationship between strength and w/cm itself held well. Given these findings, the measured influence of the w/cm on the durability factor of air-entrained concrete is small.

The pattern reverses in the absence of entrained air because for the non-air-entrained concrete tested by Lomboy and Wang (2009), the durability factor at a given freeze-thaw cycle decreased with increased w/cm. Additionally, since the concrete strength decreases as w/cm increases, the freeze-thaw durability of the concrete without air-entraining admixture increased with increased strength and decreased w/cm (Lomboy and Wang 2009). The w/cm is therefore not a significant factor that impacts the freeze-thaw resistance of properly air-entrained concrete mixtures. For non-air-entrained concrete mixtures, the w/cm is more influential and decreasing it moderately improves freeze-thaw resistance..

2.4.4. Permeability

The permeability of the concrete controls the rate at which the critical degree of saturation prerequisite discussed in Section 2.1.2.2 is approached, and it is itself governed largely by the w/cm. Lomboy and Wang (2009) tested concrete mixtures with w/cm = 0.25, 0.35, 0.45, and 0.55 and found that the rapid chloride permeability and the porosity increased with increasing w/cm, and increased more rapidly above a w/cm of 0.35. Goto and Roy (1981) found that permeability decreased exponentially with decreasing w/cm. Kim et al. (2014) quantified the sensitivity of the internal transport properties for mortar specimens with 5.2% total air content and found that increasing the w/cm from 0.45 to 0.60 increased the porosity by 50%, the chloride diffusion coefficient by 57%, the air permeability by 92%, the sorptivity by 159%, and the moisture diffusion coefficient by 166%, while the surface moisture content increased linearly by 32%. The disproportionate response of the sorptivity and moisture diffusion coefficient relative to the porosity indicates that moisture ingress accelerates faster than pore volume grows as the w/cm increases, thus indicating that the risk of reaching the critical degree of saturation increases as the w/cm increases. Kakizaki (2000) found that the permeability of high-fluidity concrete decreased with a decrease in w/cm regardless of the type of chemical admixtures used, and that the total pore volume decreased with decreasing w/cm while the number of fine pores increased, therefore indicating an improvement of the pore system. As was discussed in Section 2.1.2.1, the presence of smaller pores leads to a reduction in the initial freezing temperature threshold meaning that concrete mixtures with smaller pores will have to be exposed to colder cycles of freezing and thawing to be vulnerable to freeze-thaw damage.

Lomboy and Wang (2009) found that the durability factor of the concrete without air-entraining admixture decreased with increased rapid chloride permeability and porosity. The explanation offered is that a more permeable and porous concrete might permit more freezable water to enter, attain a higher degree of saturation when subjected to freeze-thaw testing, and therefore suffer more damage (Lomboy and Wang 2009). The relationships between freeze-thaw durability and rapid chloride permeability or porosity existed for the non-air-entrained mixtures but not for the air-entrained mixtures (Lomboy and Wang 2009). The air-entrained concrete mixtures had much higher porosity, but not much higher rapid chloride permeability, than the concrete without air-entraining admixture, since the entrained voids add pore volume without forming connected transport paths (Lomboy and Wang 2009). Results from Lomboy and Wang (2009) showed that to be freeze-thaw durable with a durability factor of at least 85, the concrete mixtures made with Type I cement and Class C fly ash required a rapid chloride permeability of 185 coulombs and a porosity of 3.4%, while the concrete made with Type IP cement required a rapid chloride permeability of 608 coulombs and a porosity of 5.0%. These results suggest that concrete mixtures without air-entraining admixture may not be freeze-thaw durable even at rapid chloride permeability values below 1,000 coulombs, with exceptions only for concrete having very low permeability and very high strength (Lomboy and Wang 2009). Low permeability therefore primarily protects concrete by lengthening the time required to reach the critical degree of saturation, but as an acceptance criterion it is meaningful only for concrete lacking an adequate air-void system. Despite the improvements in the pore structure and permeability caused by decreasing the w/cm, the relationship between permeability and durability factor is similar to that of the w/cm and durability factor. If the air-void system is adequate, the influence of permeability is negligible, while if the air-void system is inadequate, the influence of permeability is more significant.

2.4.5. Strength

It is possible that the strength of the cement paste could play a role in ensuring adequate freeze-thaw resistance of concrete mixtures since according to the theories of freeze-thaw damage discussed in Section 2.1.1, damage only occurs when internal stress exceeds the tensile strength of the cement paste. It is generally accepted that properly air-entrained concrete can sustain one freeze cycle when it has attained a compressive strength of 500 psi, and repeated cycles of freezing and thawing when saturated at a compressive strength of 3,500 psi (ACI 201.2 2023). Requiring a minimum strength before freezing helps ensure that the tensile strength of the paste is sufficient and that the fractional volume that could be occupied by freezable water in saturated concrete has been adequately reduced by the formation of hydration products (ACI 201.2 2023). While it is important that minimum strengths be achieved before the concrete is exposed to cycles of freezing and thawing, the predictive capability and influence of strength is similar to that of the w/cm and permeability. For the non-air-entrained concrete tested by Lomboy and Wang (2009), it was found that strength, in addition to permeability, plays a moderate role in ensuring freeze-thaw durability, with the concrete mixtures made with Type I cement and 15% Class C fly ash requiring a 28-day compressive strength of 10,250 psi and a w/cm of 0.19 to be freeze-thaw durable. Their concrete mixtures made with Type IP cement required 11,880 psi and a w/cm of 0.26 to be freeze-thaw durable (Lomboy and Wang 2009).

For the air-entrained concrete in the same study, the relationships between the durability factor and the strength were not clear, and although the air-entrained concrete had slightly lower strength than the non-air-entrained concrete, air-entrained concrete with a minimum 28-day compressive strength of 4,540 psi was freeze-thaw durable as long as it possessed proper air-void parameters (Lomboy and Wang 2009). Obla, Kim, and Lobo (2016) similarly found that neither the w/cm nor the strength correlated well with the durability factor. Overall, the literature reveals that like the w/cm and permeability, strength only has a moderate influence on the freeze-thaw durability of non-air-entrained concrete but has no significant influence on the freeze-thaw durability of air-entrained concrete mixtures with adequate air-void systems.

2.5 Current Freeze-Thaw Resistance Guidance

In this section, requirements and guidance from states and various national concrete standards for protecting concrete from cycles of freezing and thawing will be discussed.

2.5.1. State Highway Specifications

While the parameters of the air-void system such as the spacing factor and specific surface are essential to ensuring freeze-thaw durability, they cannot be determined by testing fresh concrete. Therefore, state departments of transportation (DOT) primarily specify a minimum total air content that is expected to ensure that the recommended spacing factor and specific surface values in ACI 201 (2023) are achieved. A survey was performed of state highway specifications of all member states and territories in the Southeastern Association of State Highway and Transportation Officials (SASHTO) region except for Hawaii and Puerto Rico to determine the minimum required total air content for bridge deck concrete. The source of the information covered herein is listed in Table 2-1. The results of this survey are shown in Figure 2-3.

Table 2-1. Sources used for the creation of Figure 2-3.

State	Source
AL	(Alabama Department of Transportation 2026)
AR	(Arkansas State Highway and Transportation Department 2014)
FL	(Florida Department of Transportation 2025)
GA	(Georgia Department of Transportation 2021)
KY	(Kentucky Transportation Cabinet 2019)
LA	(Louisianna Department of Transportation 2026)
MS	(Mississippi Department of Transportation 2017)
NC	(North Carolina Department of Transportation 2024)
OK	(Oklahoma Department of Transportation 2019)
SC	(South Carolina Department of Transportation 2025)
TN	(Tennessee Department of Transportation 2021)
TX	(Texas Department of Transportation 2024)
VA	(Virginia Department of Transportation 2020)
WV	(West Virginia Department of Transportation Division of Highways 2023)

The survey reveals that state DOTs in northern SASHTO states generally require higher minimum total air contents, while states DOTs in the southern SASHTO states require less or have no requirement in the case of Florida. This can be explained by northern SASHTO states being exposed to a cooler climate, therefore resulting in concrete structures in northern SASHTO states being exposed to more cycles of freezing and thawing than structures in southern SASHTO states.

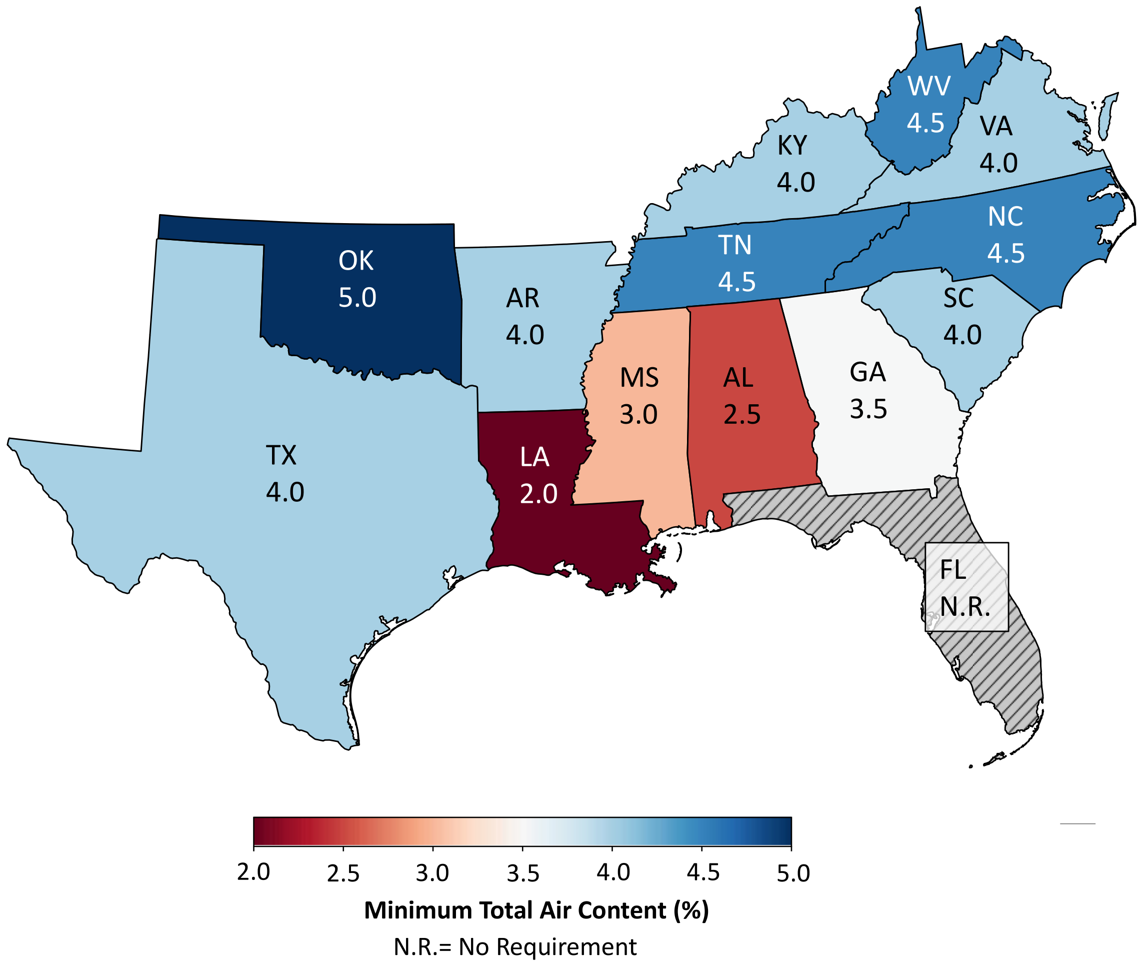


Figure 2-3. Minimum Total Air Contents of Bridge Deck Concrete Specified by State DOTs of SASHTO Member States.

2.5.2. AASHTO Specifications and Practice

While the AASHTO LRFD Bridge Design Specifications (2024) do not provide any guidance for ensuring concrete is resistant to cycles of freezing and thawing, the fourth edition of the AASHTO LRFD Bridge Construction Specifications (2017) require maximum w/cm, minimum total air contents, and strengths at 28 days depending on the class of concrete being placed. These specifications are shown for concrete classes A through C in Table 2-2. The description of each of these classes is shown in Table 2-3. The required minimum total contents for air-entrained concrete in Table 2-2 align well with the research discussed in 2.2.1. In the case of class B (AE) concrete, the minimum air content required is 3.5% which is the lowest for all air-entrained concretes per this specification.

Table 2-2. Freeze-Thaw Requirements for Concrete Classes A through C from AASHTO LRFD Bridge Construction Specifications 4th Edition (2017).

Class of Concrete	Maximum w/cm	Air Content Range (%)	Specified Compressive Strength (ksi at days)
A	0.49	--	4.0 at 28
A (AE)	0.49	6 +/- 1.5	4.0 at 28
B	0.58	--	2.4 at 28
B (AE)	0.55	5 +/- 1.5	2.4 at 28
C	0.49	--	4.0 at 28
C (AE)	0.45	7 +/- 1.5	4.0 at 28
P	0.49	[1]	≤ 6.0 at [1]

Note 1: as specified in the contract documents.

Table 2-3. Classes of Concrete in AASHTO LRFD Bridge Design Specifications (2024).

Class of Concrete	Description
A	All elements of structures, except when another class is more appropriate, and specifically for concrete exposed to saltwater.
A (AE)	When Class A concrete is needed and will be subject to alternate freezing and thawing and exposure to deicing salts, seawater, or other potentially damaging environments
B	Footings, pedestals, massive pier shafts, and gravity walls
B (AE)	When Class B concrete is needed and will be subject to alternate freezing and thawing and exposure to deicing salts, seawater, or other potentially damaging environments
C	Thin sections, such as reinforced railings less than 4.0 in. thick, for filler in steel grid floors, etc.
C (AE)	When Class C concrete is needed and will be subject to alternate freezing and thawing and exposure to deicing salts, seawater, or other potentially damaging environments
P	When strengths in excess of 4.0 ksi are required.

AASHTO R 101 (2025), the Standard Practice for Developing Performance Engineered Concrete Pavement Mixtures, has similar provisions intended to ensure freeze-thaw durability that are summarized in Table 2-4.

Table 2-4. AASHTO R 101 (2025) Freeze-Thaw Provisions for Performance Engineered Concrete Mixtures.

Provision	Value
Maximum w/cm	<0.45
Total Air Content Option 1 (choose one option)	5.0 to 8.0%
Total Air Content Option 2 (choose one option)	>4.0% and a SAM number ≤ 0.20
Cement replacement with SCMs	When $CaCl_2$ or $MgCl_2$ deicing chemicals are used, replace 30% of cement by weight with SCMs

2.5.3. ACI 318 Building Code for Structural Concrete-Code Requirements and Commentary

ACI Code-318 (2025) also has requirements for structural concrete that are designed to protect it from cycles of freezing and thawing. These requirements take into consideration the severity of the exposure of the concrete to cycles of freezing and thawing by defining exposure classes that determine which freeze-thaw requirements must be used by the engineer of record. These exposure classes are described in Table 2-5 and the requirements associated with each exposure class are shown in Table 2-6.

Table 2-5. ACI Code-318 (2025) Freeze-Thaw Exposure Classes.

Exposure Class	Description
F0	Assigned to concrete that will be not exposed to cycles of freezing and thawing
F1	Assigned to concrete that will be exposed to cycles of freezing and thawing and that will have limited exposure to water
F2	Assigned to concrete that will be exposed to cycles of freezing and thawing and that will have frequent exposure to water

Table 2-6. ACI Code-318 (2025) Freeze-Thaw Requirements by Exposure Class.

Exposure Class	Maximum w/cm	Minimum f'_c (psi)	Target Total Air Content
F0	N/A	2500	N/A
F1	0.55	3500	See Table 2-7.
F2	0.45	4500	See Table 2-7.

The nominal maximum aggregate size of the coarse aggregate used is also considered when determining which target total air content should be used since the inclusion of smaller coarse aggregate compared to larger coarse aggregate results in the concrete mixture consisting of a greater volume of cement paste that must be protected from freeze-thaw damage. This is reflected in Table 4-1, which shows that as the nominal maximum coarse aggregate size decreases, a greater target total air content should be targeted to protect the cement paste.

Table 2-7. Target Total Air Content for Difference Nominal Maximum Aggregate Sizes and Freeze-Thaw Exposure Classes from ACI Code-318 (2025).

Nominal Maximum Aggregate Size (in.)	Target Air Content (%)	
	F1	F2
3/8	6	7.5
1/2	5.5	7
3/4	5	6
1	4.5	6
1-1/2	4.5	5.5
2	4	5
3	3.5	4.5

CHAPTER 3

EXPERIMENTAL METHODS

3.1 Introduction

Two of the main objectives of this study are to determine the factors that most influence a concrete mixture's resistance to cycles of freezing and thawing and to evaluate the effectiveness of the Sequential Air Method in identifying which mixtures will be freeze-thaw resistant. To accomplish these objectives, an experimental program was designed and executed. This chapter describes the experimental program, proportions of concrete mixtures produced and tested, materials used and where they were sourced, concrete production practices, tests performed on fresh concrete, tests performed on hardened concrete, and all governing standards relating to materials, practices, and tests performed in this study.

3.2 Overview of the Experimental Program

An overview of the experimental program discussed in this section is shown in Figure 3-1.

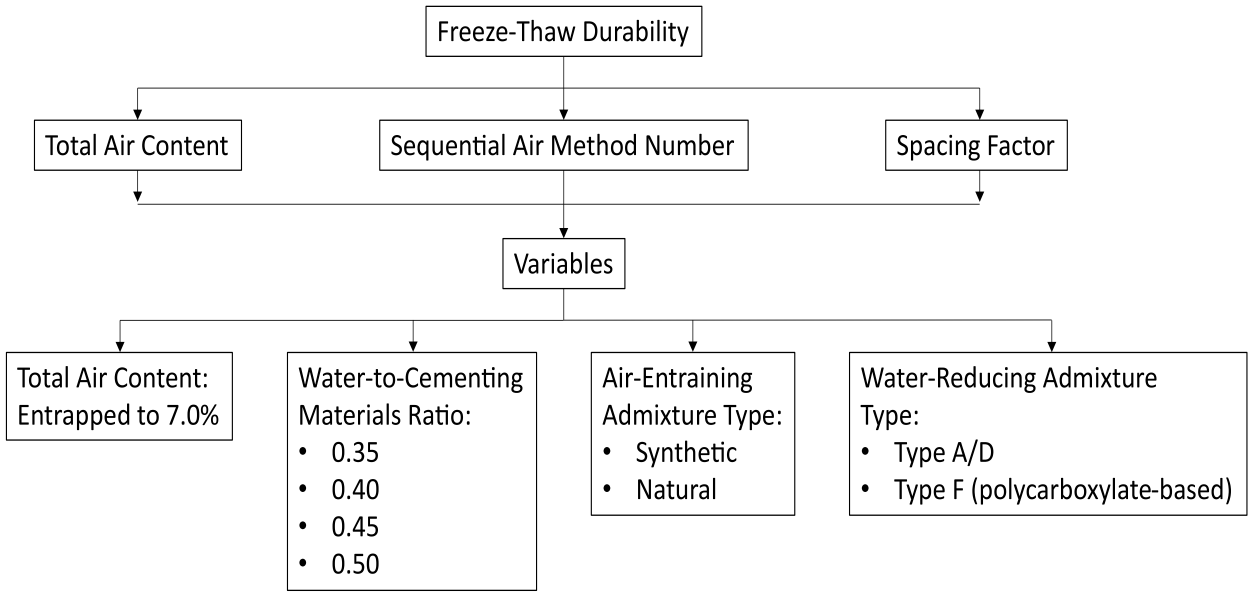


Figure 3-1. Overview of the experimental program.

To investigate the influence of total air content (TAC), w/cm, AEA type, and water-reducer type on concrete's resistance to cycles of freezing and thawing, these parameters were varied in the concrete produced in this study. The total air content was varied by changing dosages of Air-entraining admixtures. The target total air content range for mixtures produced in this study was 2.5 to 4.5%. This range was selected because a total air content range of 2.5 to 6.0% is specified in ALDOT Section 501, "Structural Portland Cement Concrete" of *ALDOT 2026 Standard Specifications for Highway Construction* (Alabama Department of Transportation 2026). Additionally, for the w/cm=0.35 mixtures, the same total air content range was targeted since ALDOT Section 513, "Prestressed Concrete Bridge Members" specifies a target air total air content of 4.5% and a maximum total air content of 6.0% (Alabama Department of Transportation 2026). Another reason that the 2.5 to 4.5% target total air content range was selected is that based on a review of other sets of freeze-thaw data, the research team identified a total air content transition range of approximately 2.5 to 4.5%, in which concrete transitions from being susceptible to freeze-thaw damage to being resistant to freeze-thaw damage. To serve as control mixtures, a few concrete mixtures were produced with no air-entraining admixtures, meaning that air in those concrete mixtures was limited to only entrapped air. A few concrete mixtures with total air contents greater than 4.5% were also tested.

Another potential factor impacting concrete's freeze-thaw resistance is w/cm. This is due to the well-established fact that the w/cm directly influences the porosity, permeability, and strength of concrete mixtures. The w/cm used in this study are 0.35, 0.40, 0.45, and 0.50. These w/cm were selected because they are common w/cm used in ALDOT structures and provide an adequate range of w/cm over which to evaluate freeze-thaw resistance. Concrete mixtures with w/cm of 0.40 to 0.50 are typically used in pavements and cast-in-place bridge components, whereas concrete mixtures with w/cm of 0.35 are typical of precast prestressed applications. Additionally, while Tanesi and Meininger (2006) and Felice, Freeman, and Ley (2014) found that the influence of w/cm on the durability factor of air-entrained concrete mixtures with adequate air-void systems was insignificant to unnoticeable, the research team wanted to further validate these findings. Moreover, by varying the w/cm, the research team was able to evaluate the relationship between strength and durability factor. However, given the fact that Lomboy and Wang (2009) could not establish a statistically clear relationship between the strength and the durability factor of the air-entrained concrete tested, a statistically significant relationship between strength and durability factor was not expected by the research team for air-entrained mixtures.

A third variable of interest to the research team was type of air-entraining admixture. Because both synthetic and natural (wood-rosin) based air-entraining admixtures are commonly used in ALDOT structures, the research team tested concrete mixtures made with both types. Another reason for the research team's decision to evaluate concrete mixtures made with both synthetic and natural air-entraining admixtures is that notable differences in the air-void systems of concrete mixtures made with different types of air-entraining admixtures have been observed over time (Freeman 2012). For instance, Freeman found that the synthetic air-entraining admixture produced concrete mixtures with the lowest spacing factor, highest specific surface, and least change in the air-void system over a period of 60 minutes compared to concrete mixtures containing natural and vinsol resin air-entraining admixtures (2012). However, despite potential differences in the air-void systems of concrete mixtures made with synthetic, natural, and vinsol resin air-entraining admixtures, Felice, Freeman, and Ley (2014), found that concrete mixtures containing low dosages (3.7 fl. oz./cwt.) of mid-range water-reducing admixture or no mid-range water-reducing admixture exhibited excellent freeze-thaw resistance as long as their total air content was at least 3.5% or 11% in the cement paste, regardless of the type of air-entraining admixture used. Given these unexpected findings, the research team decided to investigate the freeze-thaw resistance of concrete mixtures made with both synthetic and natural air-entraining admixtures to determine if excellent freeze-thaw resistance can be achieved in concrete mixtures made with both types of air-entraining admixtures.

The last potential factor evaluated for its impact on concrete's freeze-thaw resistance is type of water-reducing admixture. Given the frequent use of Type A, Type D, and Type F PC HRWR admixtures in ALDOT structures, concrete mixtures made with both Type A/D (type depends on dosage of water-reducer used) and Type F PC HRWR admixtures were tested to assess their impact on the concrete's freeze-thaw resistance. This was important to evaluate because Freeman (2012) found that the inclusion of PC HRWR admixture in some cases coarsens the air-void system, causing a higher frequency of voids with chords lengths greater than 200 micrometers and a higher spacing factor at a given total air content. Therefore, some mixtures containing PC HRWR admixtures that are expected to have adequate freeze-thaw resistance based on their total air content will fail AASHTO T 161 (2022) testing, thus highlighting a limitation of using total air content measurements when evaluating the freeze-thaw resistance of mixtures containing PC HRWR admixtures.

The experiments conducted in this research can be sorted into three categories: aggregate characterization testing, fresh concrete testing, and hardened concrete testing. It was necessary to perform aggregate characterization testing to ensure the aggregates complied with their governing AASHTO standards and to determine properties needed for proportioning. After aggregate characterization testing was completed, concrete testing began. Quality control tests were performed on fresh concrete to ensure that the slump, temperature, unit weight, and total air content were in compliance with the requirements of ALDOT Section 513 for mixtures with w/cm=0.35 and Section 501 for mixtures with w/cm=0.40, 0.45, and 0.50 (Alabama Department of Transportation 2026). The SAM number was also determined so that the research team could establish a relationship between a concrete mixture's SAM number and its durability factor. The relationships between the total air content and the SAM number with the concrete mixture's durability factor could then be compared to determine whether the total air content or the SAM number serves as a better indicator for freeze-thaw resistance. The total air content from the sequential air meter was also determined for comparison with the total air content obtained from the Type B pressure meter.

Following completion of fresh concrete testing, specimens were cured in preparation for hardened concrete testing. Hardened concrete tests performed include compressive strength testing to ensure adequate strength as specified in Sections 501 and 513 (Alabama Department of Transportation 2026), freeze-thaw testing to determine the concrete mixture's durability factor, and hardened air-void analysis to determine the mixture's spacing factor. The spacing factor was determined so that a relationship between it and the durability factor could be evaluated. The hardened air-void analysis was performed by SGS TEC Services, a construction materials testing company in Lawrenceville, Georgia using Procedure B, the modified point count method of ASTM C 457 (2024).

3.2.1. Mixture Identification System

Figure 3-2 illustrates the mixture ID system used in this study which includes the w/cm, water-reducing admixture type, air-entraining admixture type, and batch number. For example, the mixture ID shown in Figure 3-2 represents the second concrete mixture with w/cm=0.35 made with the PC HRWR admixture PC1 and a natural (wood-rosin based) air-entraining admixture. If no air-entraining admixture was used, as was the case for control mixtures, the mixture ID only contains the w/cm, the water-reducing admixture type, and the batch number.

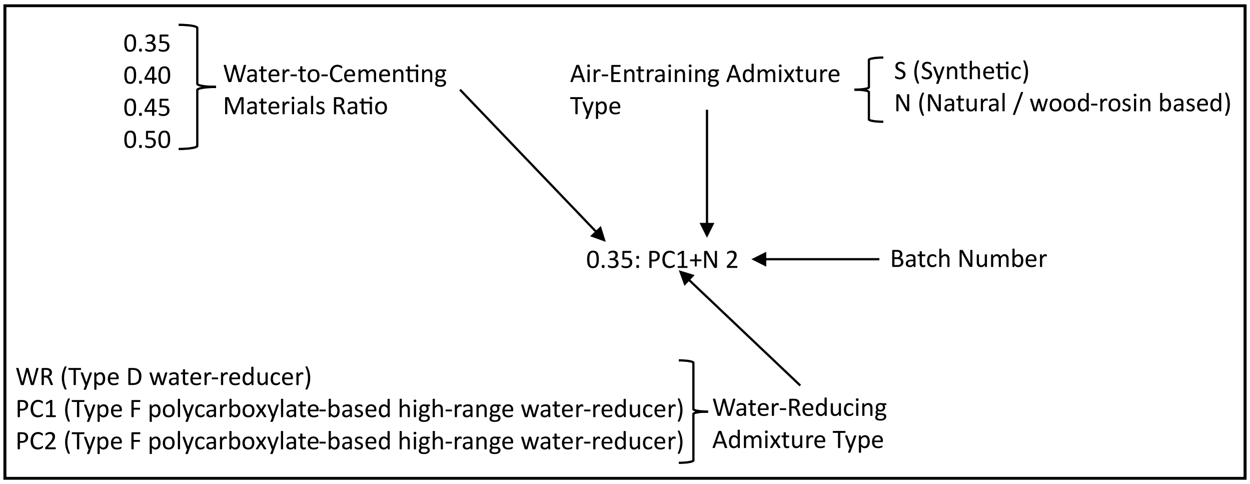


Figure 3-2. Mixture ID system.

3.3 Mixture Proportions

This study utilized concrete mixtures formulated to meet the requirements of Sections 501 and 513 of *ALDOT 2026 Standard Specifications for Highway Construction* (Alabama Department of Transportation 2026). Concrete mixtures with four water-to-cementing materials ratios (w/cm) of 0.35, 0.40, 0.45, and 0.50 were produced. The mixture with w/cm=0.35 was formulated to meet the requirements of Section 513 while the mixtures with w/cm=0.40, 0.45, and 0.50 were formulated to meet the requirements of Section 501. Table 3-1 shows the saturated-surface dry (SSD) mixture proportions of the concrete produced in this study. The mixtures produced without air-entraining admixtures (Mixture IDs: 0.35: PC1, 0.35: PC2, and 0.45: WR) serve as controls to determine the freeze-thaw resistance of non-air-entrained concrete that contains only entrapped air and allow for comparison with air-entrained mixtures. The assumed air content influences the weight of sand batched since the volume of sand is calculated by subtracting the volume of all the mixture's constituents (except for the sand) from the total volume of a unit of concrete, which in this case is one cubic yard.

Table 3-1. Mixture proportions of concrete produced in this study.

Mixture ID	w/cm	Cement (lb/yd³)	Fly Ash (lb/yd³)	SF (lb/yd³)	CA[1] (lb/yd³)	FA[1, 2] (lb/yd³)	Water (lb/yd³)	Adm.
0.35: PC1	0.35	663	0	42	1885	1111	247	PC1
0.35: PC2	0.35	663	0	42	1885	1111	247	PC2
0.35: PC1+S	0.35	663	0	42	1885	1111	247	PC1+S
0.35: PC1+N	0.35	663	0	42	1885	1111	247	PC1+N
0.35: PC2+S	0.35	663	0	42	1885	1111	247	PC2+S
0.4: WR+S	0.40	464	199	0	1800	1162	265	WR+S
0.45: WR	0.45	434	186	0	1800	1163	279	WR
0.45: WR+N	0.45	434	186	0	1800	1163	279	WR+N
0.45: WR+S	0.45	434	186	0	1800	1163	279	WR+S
0.5: WR+S	0.50	395	169	0	1900	1107	282	WR+S

1 Aggregates are in saturated surface-dry state.
2 Total air content of 4.5% for all mixtures.

Air-entraining and water-reducing admixture dosages for each mixture can be found in Appendix B.

3.4 Materials

The constituent materials of concrete mixtures tested in this study were coarse aggregate (CA), fine aggregate (FA), Class C fly ash (FA_C), silica fume (SF), water, and portland limestone cement. For this project, Type IL blended cement from Argos was used. Aggregates used are from approved sources listed on Alabama Department of Transportation (ALDOT) List I-1. The coarse aggregate used was Type I crushed limestone from Vulcan Materials Company with the ALDOT List I-1 ID number being 0497 (10218) obtained from the Huntsville area. Its nominal maximum aggregate size was ¾ inches. The fine aggregate used was a Type I concrete sand from Foley Materials Company with an ALDOT List I-1 ID number of 1767 (10178).

Silica fume was used at a 6% replacement by weight of cement level in concrete mixtures with w/cm=0.35. Silica fume was included in w/cm=0.35 mixtures due to the necessity for w/cm=0.35 concrete mixtures to have higher strengths due to their intended use in prestressed concrete applications. Additionally, mixtures containing silica fume exhibit increased early-age strength due to the fineness of the silica fume and increased long-term strength due to the pozzolanic nature of the silica fume. The increased early-age strength is advantageous for prestressed concrete producers since it allows them to remove members from casting beds more quickly. Moreover, concrete made with silica fume has a denser microstructure, significantly lower permeability, increased durability caused by the lower permeability, less weak and water-soluble calcium hydroxide, and greater calcium-silicate-hydrate (CSH) content (S. Kosmatka and Wilson 2016; Mehta and Monteiro 2014). The 6% replacement level was chosen because it is less than the 10% maximum allowed by ALDOT Section 513 (Alabama Department of Transportation 2026) but substantial enough to ensure that the desirable properties of concrete mixtures made with silica fume listed above are achieved.

Class C fly ash was used at a 30% replacement by weight of cement level in concrete mixtures with w/cm=0.40, 0.45, and 0.50. The decision was made to include Class C fly ash due to several factors. Concrete made with Class C fly ash has a lower carbon footprint than concrete made with only portland cement since Class C fly ash is a by-product of the combustion of coal in coal-fired powerplants while the production of portland cement is an energy-intensive process that releases a substantial amount of carbon dioxide into the atmosphere (Mehta and Monteiro 2014). Additionally, concrete made with Class C fly ash has a lower water demand, has a lower rate of heat release, has lower permeability, and potentially has greater long-term strength than concrete made with only portland cement depending on curing conditions (S. Kosmatka and Wilson 2016). These improvements in permeability and long-term strength are due to the partially pozzolanic behavior of Class C fly ash. The 30% replacement level was selected because it is the maximum permitted by ALDOT 501 (Alabama Department of Transportation 2026), and exceeding the limit would result in an excessive reduction in early-age strength.

Table 3-2 shows the materials used, the source, the applicable governing AASHTO or ASTM standard, and in which concrete mixture(s) the material was used.

Table 3-2. Materials used in this Study.

Material	Source	Standard	Mixture(s)
Type IL Cement	Argos	AASHTO M 240	0.35, 0.40, 0.45, and 0.50
Coarse Aggregate	Vulcan Materials Co.	AASHTO M 80	0.35, 0.40, 0.45, and 0.50
Fine Aggregate	Foley Materials Co.	AASHTO M 6	0.35, 0.40, 0.45, and 0.50
Class C Fly Ash	EM Resources LLC	AASHTO M 295	0.40, 0.45, and 0.50
Silica Fume	Elkem Materials	AASHTO M 307	0.35
Water	Auburn City Water	ASTM C1602	0.35, 0.40, 0.45, and 0.50

Aggregate properties were verified through standardized testing to confirm compliance with AASHTO M 6 (2022) and AASHTO M 80 (2021) and to obtain properties for use in concrete batching procedures. Figure 3-3.

Table 3-3 shows all the standard tests performed on coarse and fine aggregates used in this study. The coarse aggregate gradation as well as the ALDOT Section 801 (2026), "Coarse Aggregates" upper and lower limits for a #67 gradation are shown in Figure 3-3.

Table 3-3. Aggregate Tests performed in this study and their AASHTO Standards.

Aggregate Tests Performed	Standard
Coarse Aggregate Bulk density (unit weight) and Voids in Aggregate	AASHTO T 19 (2024)
Coarse and Fine Aggregate Sieve Analysis	AASHTO T 27 (2024)
Fine Aggregate Specific Gravity and Absorption	AASHTO T 84 (2022)
Coarse Aggregate Specific Gravity and Absorption	AASHTO T 85 (2022)

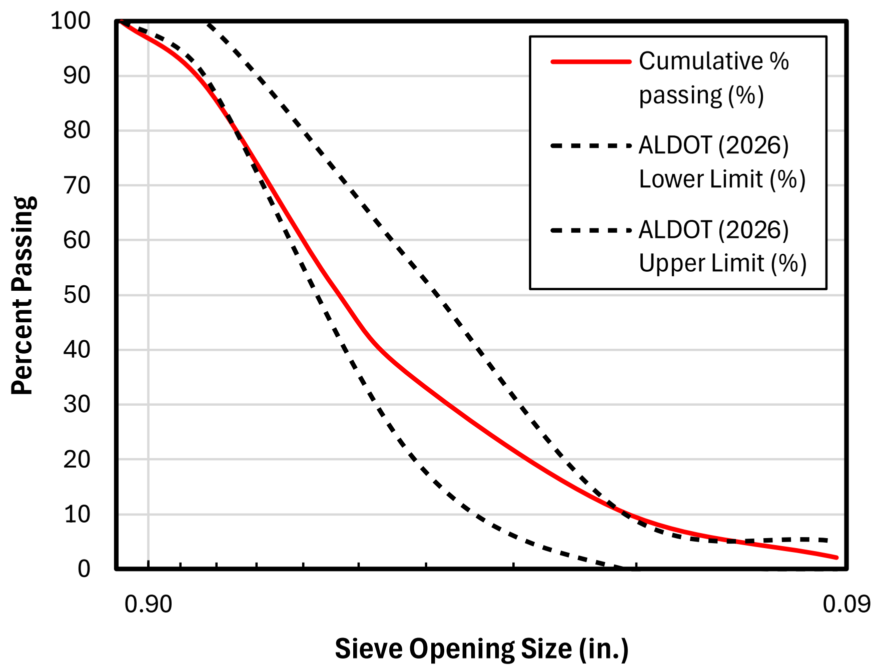


Figure 3-3. Coarse aggregate gradation.

The fine aggregate gradation as well as the ALDOT Section 802, "Fine Aggregates" upper and lower limits for fine aggregate (concrete sand) as shown in Figure 3-4 (2026). Table 3-4 shows the bulk specific gravity, bulk SSD specific gravity, and absorption capacity of the aggregates used in this study. Also shown are the coarse aggregate's dry-rodded unit weight and the fine aggregate's fineness modulus.

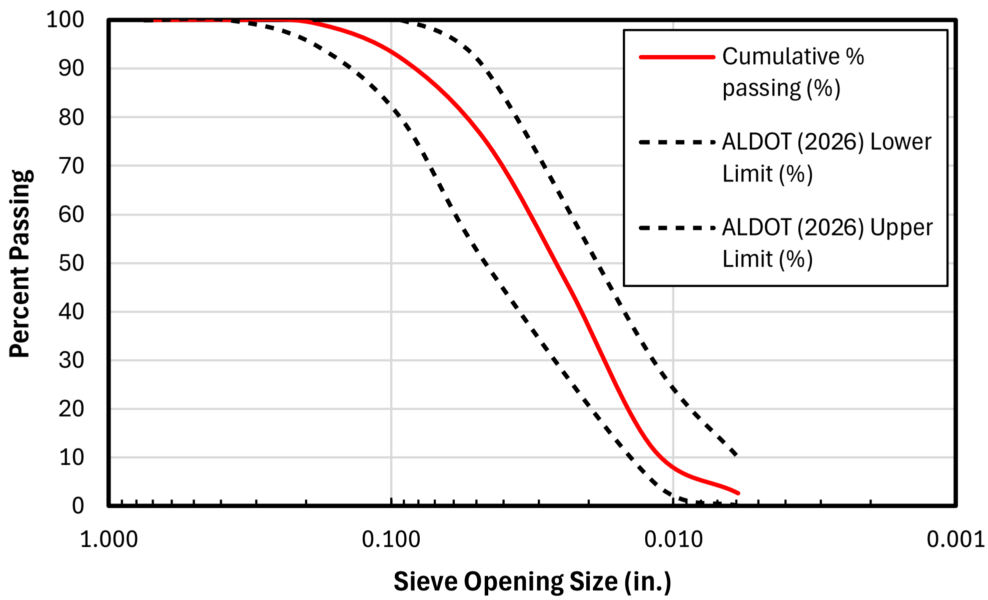


Figure 3-4. Fine aggregate gradation.

Table 3-4. Properties of coarse and fine aggregates used in this study.

Property	Material	
	Coarse Aggregate (CA)	Fine Aggregate (FA)
Dry-Rodded Unit Weight (lb/ft^3)	93	--
Bulk Specific Gravity	2.644	2.584
Bulk SSD Specific Gravity	2.667	2.608
Absorption Capacity (%)	0.86	0.66
Fineness Modulus	--	2.74

Chemical admixtures compliant with AASHTO standards were also used to modify the properties of the concrete, specifically the total air content and the workability. Table 3-5 summarizes the admixtures, sources, governing standards, and concrete mixtures containing these admixtures. Type A water reducers reduce the water demand needed to maintain a certain level of workability by 5 to 10% while Type D water reducers perform the same function while also retarding the setting of the concrete. Type F water reducers are high-range water-reducing (HRWR) admixtures, also known as superplasticizers, that reduce the water demand by 12 to 40%.

Table 3-5. Admixtures used in this study.

Description	Symbol	Product	Source	Standard	Mixture(s)
Synthetic AEA	S	MasterAir AE 200	Master Builders Solutions	AASHTO M 154	0.35, 0.40, 0.45, and 0.50
Natural AEA	N	MasterAir AE 90	Master Builders Solutions	AASHTO M 154	0.45
Type A/D WR[1]	WR	MasterPozzolith 322	Master Builders Solutions	AASHTO M 194	0.40, 0.45, and 0.50
Type F WR	PC1	MasterGlenium 7920	Master Builders Solutions	AASHTO M 194	0.35
Type F WR	PC2	MasterGlenium 7960	Master Builders Solutions	AASHTO M 194	0.35

1 Water-reducing admixture qualifies as both a Type A and Type D water-reducer depending on dosage. Dosage varied in this study to produce concrete with adequate slump.

3.5 Concrete Production

3.5.1. Pre-Batch Preparations

Prior to batching, moisture corrections were performed on aggregates in accordance with AASHTO T 255 (2025). Aggregates from the top, middle, and bottom layers of their stockpiles were mixed and placed into buckets. The silos from which the aggregates were taken are shown in Figure 3-5. To perform moisture corrections, one extra bucket was filled with coarse aggregate, and another was filled with fine aggregate. On the day of batching, the aggregates in the extra buckets were dumped into a wheelbarrow, mixed to obtain a representative sample of 1000 grams, and put into pots to be heated.

Figure 3-5. Aggregate silos.

Heating continued for approximately 30 minutes, at which point the aggregates were reweighed. Following this, at 5-minute intervals the aggregates were reweighed to determine if the change in moisture content was less than 0.1%. If so, the aggregates were considered dry and the moisture content determined. The remaining buckets of aggregate were weighed, and the amount of aggregate in them was adjusted to meet that required for batching, considering the batch size and their moisture contents. Cement, supplementary cementing material, and water were also weighed out in buckets prior to batching. The weight of water was also adjusted based on the moisture contents of the aggregates.

Next, a buttering mixture of fine aggregate, cement, and water was placed in a running concrete mixer, shown in Figure 3-6. This was done to coat the interior surfaces of the mixer to prevent cement paste from the concrete that was to be tested from sticking to the mixer. If this was not done, a volume of cement paste would be lost, thereby altering the constituents of the tested concrete.

Figure 3-6. Mixer used for batching concrete in this study.

Next, the mixer was turned on to allow the buttering mixture to coat all the dry surfaces of the inside of the mixer. Once the mixer had been coated with the buttering mixture, it was then emptied.

Simultaneously, another member of the research team agitated admixture(s) used in the batch to redistribute settled solid particles in the admixture(s) and to ensure uniform concentration of solids prior to dispensing. This agitation was done by turning the buckets of admixtures on their sides and rolling them down and back along a 20-foot-long hallway. After agitation, the admixture was poured into a 3x6 in. cylinder (one per admixture) where it sat until it was withdrawn into the dispensing syringes.

3.5.2. Mixing Procedures

The mixing procedures implemented by the research team followed ASTM C192 (2026) with a few modifications. For the w/cm=0.35 mixtures, the mixing procedure was as follows:

1. All coarse aggregates were added to the mixer.
2. 80% of water was added.
3. Silica fume was added into the revolving mixer.
4. The mixer was run for 3 minutes.
5. All fine aggregates were added.
6. All AEA was added to the running mixer.
7. The mixer was run for 3 minutes.
8. All cement was added to the running mixer.
9. The mixer was run for 1.5 minutes.
10. All PC HRWR admixture was dispersed in the remaining mixing water (20%) and poured into the mixer.
11. The mixer was run for 3 minutes.
12. The mixture was allowed to rest for 3 minutes.
13. The mixer was run for 2 minutes.

The slump, unit weight, and total air content of the concrete were determined. If either the slump or the total air content was deemed unacceptable, additional air-entraining or water-reducing admixtures were added to the mixture. The mixer was then run for 3 minutes, followed by 3 minutes of resting and 2 minutes of mixing.

For the w/cm=0.40, 0.45, and 0.50 mixtures, the mixing procedure was as follows:

1. All coarse and fine aggregates were added to the mixer. Buckets of coarse and fine aggregates were added in an alternating order.
2. 80% of water was added to the mixer.
3. The mixer was run for 3 minutes.
4. All AEA was added to the mixer while it was running.
5. The mixer was run for 3 minutes.
6. The cement and Class C fly ash were added to the mixer.
7. The water-reducer was dispersed in the remaining mixing water (20%) and poured into the running mixer.
8. The mixer was run for 3 minutes.
9. The mixture was allowed to rest for 3 minutes.
10. The mixer was run for 2 minutes.

The slump, unit weight, and total air content of the concrete were then determined. If either the slump or the total air content was deemed unacceptable, additional air-entraining or water-reducing admixtures were added to the mixture. The mixture was then mixed for 2 minutes, allowed to rest for 1 minute, and mixed again for 1 minute.

3.6 Fresh Concrete Property Testing

3.6.1. Batching and Batch-Day Tests

On batch days, several tests were performed on fresh concrete. These tests and their governing standards are shown in Table 3-6.

Table 3-6. Tests performed on fresh concrete.

Test Description	Standard
Slump	AASHTO T 119
Temperature	AASHTO T 309
Total Air Content of Concrete by Pressure Method	AASHTO T 152
Unit Weight, Yield, and Gravimetric Air Content of Concrete	AASHTO T 121
Sequential Pressure Method	AASHTO T 395

The setup for the slump test was performed in accordance with AASHTO T 119 (2023). The total air content was determined in accordance with AASHTO T 152 (2024) using a Type B pressure meter made by Humboldt Manufacturing Company shown in Figure 3-7.

3-8.

Figure 3-7. Type B pressure meter used in this study.

Following the determination and acceptance of the slump and total air content of concrete, most of the concrete in the mixer was dumped into a wheelbarrow and moved into an open room for temperature measurement, SAM testing, and prism and cylinder creation. Three 3x4x16 in. prisms were cast for freeze-thaw testing in addition to one 4x8 in. cylinder for hardened air-void analysis. Six 6x12 in. cylinders were cast for compressive strength testing at 28 and 56 days. These were made in accordance with AASHTO R 39M/R 39 (2023). The layout of all equipment used for fresh concrete testing and prism and cylinder creation is shown in Figure 3-8.

Figure 3-8. Layout for fresh concrete testing and prism and cylinder creation.

The sequential air meter (SAM), used for AASHTO T 395 (2024) testing was made by Humboldt Manufacturing Company. It is shown in Figure 3-9.

Figure 3-9. Sequential air meter (SAM) made by Humboldt Manufacturing Company.

The SAM test was performed in accordance with AASHTO T 395 (2024), and the steps of performing this test are listed below:

1. The meter is filled up with concrete in the same way a Type B pressure meter is filled up:
    a. The bottom of the meter is filled 1/3 of the way full, rodded 25 times with a 5/8 in. tamping rod, and struck with a mallet 12 times.
    b. This process is repeated 3 times until the bottom of the meter is full.
    c. The top of the meter is struck off using a strike-off plate.
    d. The top rim of the meter is cleaned.
2. The top of the meter is secured to the bottom by closing opposite clamps simultaneously.
3. The petcocks are opened, and water is inserted into one of the petcocks until mostly clear, bubbleless water flows out of the opposing petcock.
4. The top chamber of the meter is pressurized to 14.5 ± 0.05 psi.
5. The petcocks are closed.
6. The lever on the top of the meter is pressed to allow the pressure in the top and bottom chambers to equalize. While the lever is pressed, the bottom chamber is struck on all sides using a rubber mallet. While holding down the lever, the “enter” button on the meter gauge should be pressed. The meter display will count down from 10 seconds, after which time the meter will display the messages “read” and “ok.” Once these messages appear, the lever may be released.
7. The “enter” button is then pressed to view the total air content.
8. “Enter” is then pressed again.
9. The pump is used to increase the pressure in the top chamber to 30.0 ± 0.05 psi.
10. Step 6 is repeated.
11. “Enter” is pressed.

12. The pump is used to increase the pressure in the top chamber to 45.0 $\pm$ 0.05 psi.

13. Step 6 is repeated.

14. One petcock is opened to release the pressure to a pressure of 14.5 psi or less.

15. Both petcocks are opened.

16. Water is inserted through one petcock until it flows out of the other one.

17. Both petcocks are closed.

18. The "enter" button is pressed.

19. The pump is used to increase the top chamber's pressure to 14.5 $\pm$ 0.05 psi.

20. The "enter" button is pressed.

21. Step 6 is repeated.

22. The pump is used to increase the top chamber's pressure to 30.0 $\pm$ 0.05 psi.

23. Step 6 is repeated.

24. The pump is used to increase the top chamber's pressure to 45.0 $\pm$ 0.05 psi.

25. Step 6 is repeated.

26. Press "enter" to view the SAM number and total air content.

Figure 3-10 illustrates the sequence of pressure steps taken in the operation of the SAM.

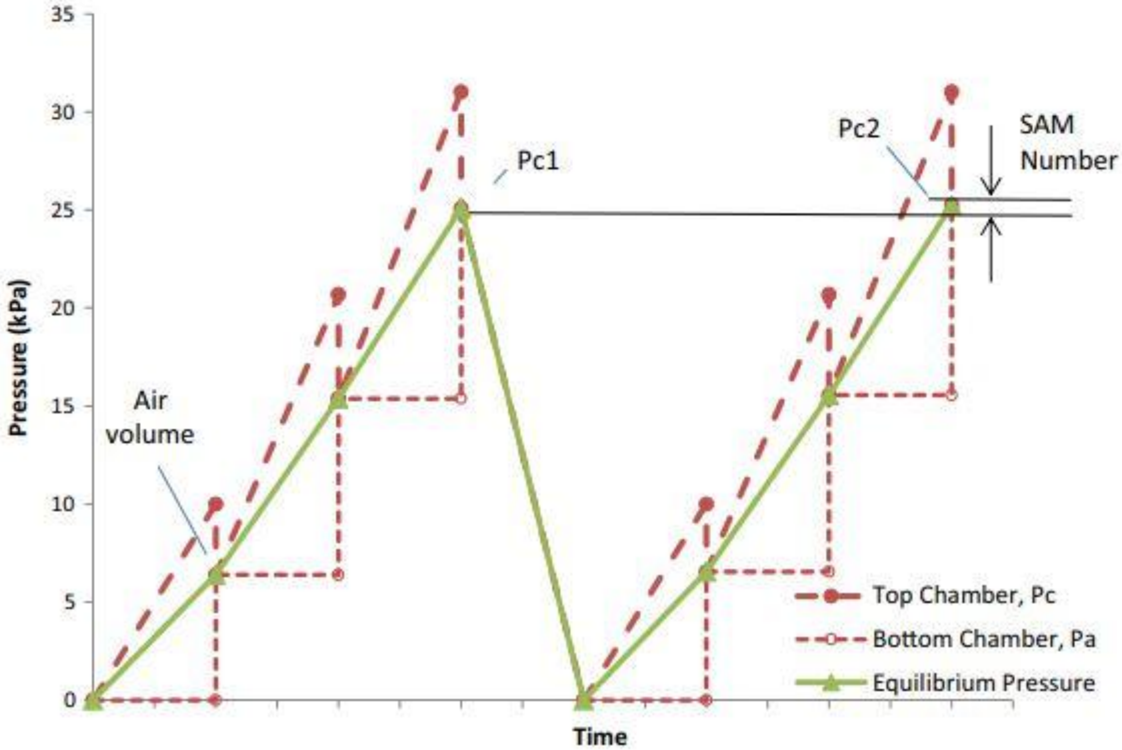


Figure 3-10. Pressure steps taken in the execution of the SAM test (Adapted from Ley, Welchel, Peery, and LeFlore, 2017).

Following the conclusion of the first total air content test using the Type B pressure meter and the determination of the SAM number, the mixer was run for 2 minutes, allowed to rest for 1 minute, and ran again for 1 minute. The remaining concrete was tested a second time to determine a second total air content from the Type B pressure meter, a second total air content from the SAM, and a second SAM number from the SAM. The total air content was determined in accordance with AASHTO T 152 (2024), and the SAM was operated in accordance with AASHTO T 395 (2024). Upon completion of fresh concrete testing, specimens were demolded after approximately 24 hours of initial curing and cured for the periods described in the following section.

3.7 Curing

After approximately 24 hours of initial curing, the prisms and cylinders were removed from the molds. The cylinders were placed in a moist room that had a relative humidity of 100% and was kept at a temperature of 73°F in accordance with AASHTO R 39M/R 39 (2023). This moist room met the requirements of AASHTO M 201 (2025) and is shown in Figure 3-11.

Figure 3-11. Moist room used for curing concrete cylinders.

The 4x8 in. cylinders were cured for at least 14 days before they were sent to a laboratory for hardened air void analysis. For each batch of concrete, three 6x12 in. cylinders were cured for 28 and 56 days, respectively before compressive strength testing was performed.

The prisms were cured in a lime-saturated water bath shown in Figure 3-12 to prevent leaching of calcium hydroxide from the concrete in accordance with AASHTO R 39M/R 39 (2023). In accordance with AASHTO T 161 (2022), the prisms were cured for 13 days before they were subjected to freeze-thaw testing.

Figure 3-12. Hydrated lime-saturated water bath used to cure freeze-thaw testing prisms.

3.8 Hardened Concrete Test Methods

3.8.1. Hardened Concrete Testing

Compression tests were performed in accordance with AASHTO T 22 (2017) after 28 and 56 days of moist curing. The apparatus used to perform compression tests was manufactured by Forney and is shown in Figure 3-13. To prevent stress concentrations from developing and to ensure a uniform distribution of load from the test apparatus to the cylinders, neoprene pads made by M.A. Industries, Inc. with a durometer of 70 were used to cap the cylinders. These were made in accordance with ASTM C1231 (2023) and were restrained from excessive lateral expansion by metal retaining rings. These tests were performed to ensure that concrete mixtures produced in this study met the minimum compressive strength prequalification requirements found in ALDOT Section 501 (Alabama Department of Transportation 2026). To verify sufficient strength, the 28-day strength was compared to the target compressive strength calculated according to Section 4.3 of ALDOT 170-82 (ALDOT 2024), the *Method of Controlling Concrete Operations for Portland Cement Concrete*.

Figure 3-13. Compression test apparatus used in this study.

After 13 days of curing in a lime-saturated bath, prisms were taken out and placed in a 40°F water bath until their internal temperature reached 38-44°F. The freeze-thaw test was then conducted in accordance with Procedure A of AASHTO T 161 (2022). This test consists of determining the relative dynamic modulus of elasticity (RDME) of the prisms after being subjected to cycles of freezing and thawing. It is calculated in accordance with Equation 2-2, as covered in Section 2.2.2.

The transverse frequency was determined by striking the test prism in the SSD condition with a small hammer and having an accelerometer attached by putty to the outside surface to measure the fundamental transverse frequency. The setup for this test is shown in Figure 3-14.

Following this test, prisms were placed in the freeze-thaw machine chamber, shown in Figure 3-15. They were then submerged in water that extended above their top surfaces by approximately 1/32 – 1/8 in.

Figure 3-14. Relative dynamic modulus of elasticity test.

Figure 3-15. Inside chamber of freeze-thaw machine filled with frozen prisms.

The machine then cooled the 40°F prisms to 0°F, after which point it heated the prisms back to 40°F over a period lasting between 3.5 to 5.0 hours. After the prisms reached 40°F, there was 10-minute period of neither heating nor cooling. This process of cooling and heating constitutes one freeze-thaw cycle. After a maximum of 36 of these cycles, the prisms were taken out for relative dynamic modulus of elasticity testing.

After any prism's relative dynamic modulus of elasticity fell below 60%, it was considered to have failed the freeze-thaw test. Its durability factor, DF, could then be calculated by the following equation given in AASHTO T 161 (2022):

$$DF = PN/M \quad \text{(Equation 3-1)}$$

where:

DF = durability factor of the test specimen;

P = relative dynamic modulus of elasticity at N cycles, (%);

N = number of cycles at which P reaches the specified minimum value for discontinuing the test or the specified number of cycles at which exposure is to be terminated, whichever is less; and

M = specified number of cycles at which the exposure is to be terminated.

As per AASHTO T 161 (2022), 300 cycles are used, hence $M = 300$. Once the durability factor for all three prisms had been determined, the average of the durability factors was calculated and reported.

Lastly, eight 4x8 in. cylinders were subjected to hardened air-void analysis. This was performed by SGS TEC Services, a construction materials testing company in Lawrenceville, Georgia. This analysis was performed in accordance with Procedure B, the modified point count method, of ASTM C 457 (ASTM 2024b) in order to determine the hardened air content, spacing factor, and specific surface. The eight cylinders are shown in Figure 3-16.

Figure 3-16. Cylinders sent for hardened air-void analysis.

The hardened air-void test procedure consisted of sawcutting each cylinder perpendicular to its top surface, grinding and polishing the cross section, and sawcutting parallel to the top surface to reduce the length of each section. One of the prepared sections is shown in Figure 3-17. A digital microscope was then used at a magnification of 150X to perform the hardened air-void analysis.

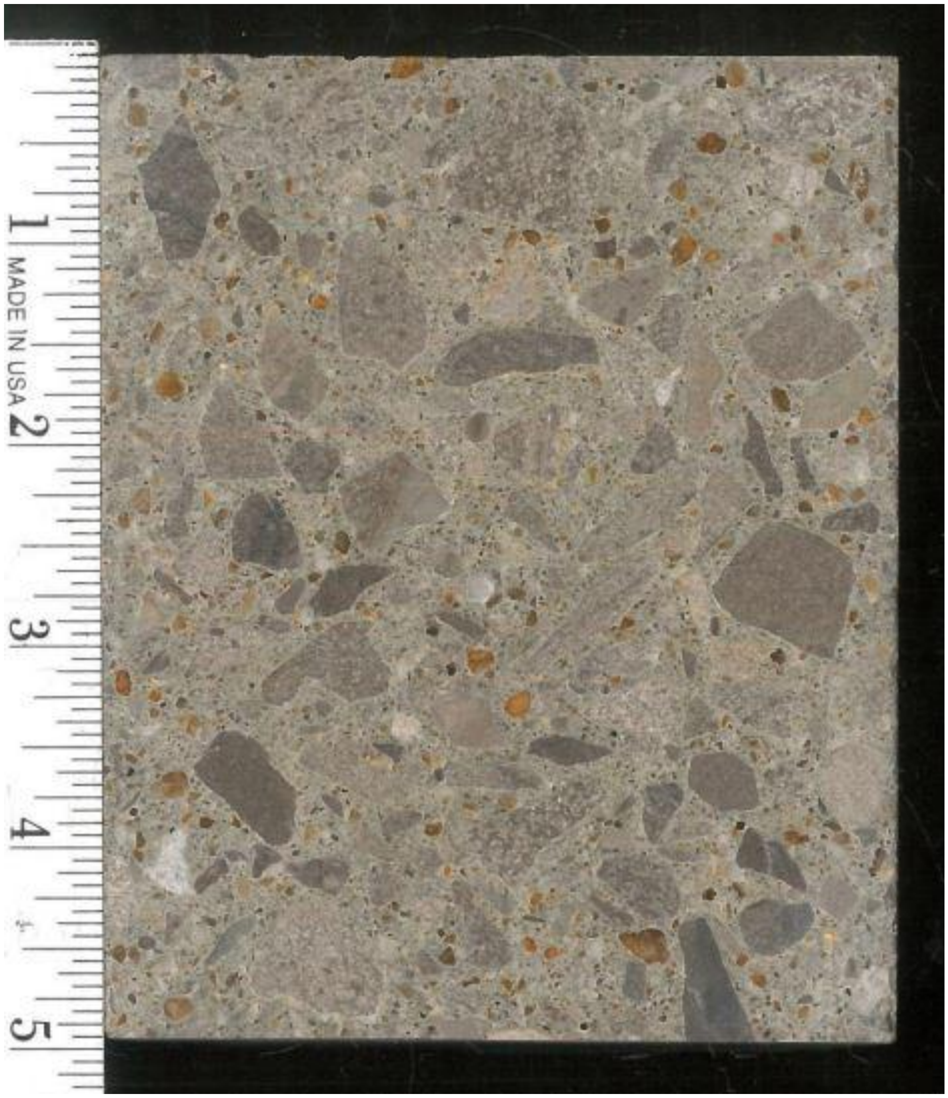


Figure 3-17. Scanned image of polished section ready for hardened air-void analysis (adapted from (SGS TEC Services 2026)).

CHAPTER 4

RESULTS AND DISCUSSION OF META-ANALYSIS OF LITERATURE-DERIVED DATA

4.1 Introduction

In this chapter, data collected from literature are analyzed and discussed. The data was analyzed by three methods: 1) categorical analysis which includes splitting the data into quadrants based on thresholds and grouping results into categories, 2) multivariable linear regression analysis, and 3) logistic regression analysis. An introduction to analysis methods 2 and 3 is included in Section 4.2. The quadrants described in analysis method 1, categorical analysis, include quadrants for true positive, true negative, false positive, and false negative results. Concrete mixtures that are correctly predicted to pass AASHTO T 161 (2022) testing based on a criterion such as their total air content are assigned to the true positive quadrant. Mixtures that are correctly predicted to fail AASHTO T 161 (2022) testing are assigned to the true negative quadrant. Mixtures that are incorrectly predicted to pass AASHTO T 161 (2022) testing are assigned to the false positive quadrant. Mixtures that are incorrectly predicted to fail AASHTO T 161 (2022) testing are assigned to the false negative quadrant. An optimized total air content threshold, defined as the total air content threshold that best accomplishes the dual goals of minimizing the amount of non-durable concrete that is placed and accepted in the field and minimizing the amount of durable concrete that is rejected in the field, was determined for target durability factors of 60 and 80. Also, relationships between the total air content, spacing factor, SAM number, and durability factor are established and evaluated. In the multivariable linear regression analysis and logistic regression analysis, the impact and significance of variables such as total air content, w/cm, SAM number, type of air-entraining admixture used, and the use of PC HRWR admixture are investigated.

4.2 Analysis Techniques of Data Obtained from Literature

Concrete mixture data and testing results were compiled from studies that investigated concrete's freeze-thaw resistance via AASHTO T 161 (2022). This subsection details the methods by which this data was analyzed.

4.2.1. Multivariable Linear Regression Analysis

The first method by which this data was analyzed is multivariable linear regression analysis. This was done to determine which factors impact the concrete's freeze-thaw resistance and the magnitude of their impact. The factors evaluated and their definitions are shown in Table 4-1.

Table 4-1. Factors investigated in multivariable linear regression analysis.

Factor	Definition
S_AEA_A	Use of synthetic air-entraining admixture as opposed to natural (wood-rosin based) air-entraining admixtures
PC_HRWR_A	Use of polycarboxylate-based high-range water-reducing admixture as opposed to other types of water-reducing admixtures
w/cm	Water-to-cementing materials ratio
TAC (%)	Total air content (%)
<x% TAC	Threshold total air content (%)
w/cm x TAC (%)	Interaction between w/cm and TAC (%)
SF (in.)	Spacing factor (in.)
>x in. SF	Threshold spacing factor (in.)

Note: < and > denote a variable dependency on a threshold.

The threshold factors <x% TAC and >x SF (in.) check whether a condition is satisfied and if so, what the impact on the durability factor is. For the factor <x% TAC, the analysis determines if the total air content being less than the threshold specified in the results table has a statistically

significant impact on the durability factor. For the factor >x SF (in.), the analysis determines if the spacing factor being greater than the threshold specified in the results table has a statistically significant impact on the durability factor.

The interaction factor w/cm x TAC (%) checks whether the influence of the w/cm on the durability factor depends on the total air content. If there is found to be a statistically significant interaction, this would imply that the effect changing the w/cm ratio has on the durability factor depends on the total air content (Montgomery et al. 2021).

The analysis was performed using a Microsoft Excel add-in called Analysis ToolPak – VBA. It uses a method called least-squares estimation to solve for coefficients in the following linear equation:

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \ldots + \beta_n x_n + \varepsilon \qquad \text{(Equation 2-1)}$$

where:

y = dependent variable (in this case durability factor),

β_0 = intercept / constant,

β_i = regression coefficient,

x_i = independent variable (e.g. total air content), and

ε = error term.

The β_0 constant is the intercept of the regression plane. If all the independent variables equal zero, β_0 is the mean of the dependent variable y (durability factor) when all the independent variables equal zero (Montgomery et al. 2021). However, because none of the concrete obtained from literature has a total air content equal to 0%, β_0 has no physical significance. For this reason, β_0 values for each regression model were not reported.

For every independent variable investigated in each model there is a corresponding regression coefficient (β_i) and x term (x_i). The interpretation of the coefficient β_i is that there is a change in the mean of the distribution of y (durability factor) equal to β_i caused by a unit change in x_i, holding all other variables constant (Montgomery et al. 2021). If the independent variables are standardized before the analysis is done as was the case in this study, one can compare the magnitude of the coefficients to determine the relative influence of each independent variable on the dependent variable. If standardization occurred, a one-standard deviation change in x_i would indicate a predicted change durability factor by β_i standard deviations. In the case of categorical independent variables such as the type of air-entraining admixture or the type of water-reducing admixture, β_i indicates the change in durability factor caused by the presence of the independent variable compared to its alternative. For example, a β_i = 0.2 value for the S_AEA_A variable indicates that concrete made with a synthetic air-entraining admixture is predicted to have a durability factor that is 0.2 standard deviations greater than concrete made with a natural (wood-rosin based) air-entraining admixture. Likewise, a β_i = -0.2 value for the PC_HRWR_A variable indicates that concrete made with PC HRWR admixture is expected to have a durability factor that is 0.2 standard deviations less than concrete without using PC HRWR admixture.

The ε error term is a term associated with random errors. In multiple linear regression analysis, it is required that the random errors are independent, randomly distributed, and follow a normal distribution with a mean equal to zero (Montgomery et al. 2021). Because $\varepsilon = 0$ is an underlying assumption of the analysis, ε was not reported in the analysis results.

Other than the regression coefficients, the adjusted R^2, standard error of the regression, significance F, *p*-values, and *t*-statistics were also reported. The decision was made to report the adjusted R^2 instead of the more common R^2 because the adjusted R^2 only increases upon the addition of variables that reduce the residual mean square (the error) of the model (Montgomery et al. 2021). Additionally, the adjusted R^2 decreases upon the addition of non-statistically significant variables to the model, thus allowing the research team to better identify which variables influence the durability factor. The standard error of the regression, also known as the root mean square error of the regression, has the same units as the dependent variable y (durability factor) (Montgomery et al. 2021). Because both the independent and dependent variables were standardized prior to analysis, the standard error has the units of standard deviations of the dependent variable (durability factor). Therefore, a standard error of 0.5 would indicate that the model typically mispredicts the durability factor by +/- 0.5 standard deviations. The significance F is also known as the *p*-value of the regression and is used to determine if the group of independent variables as a whole accurately predict the dependent variable (Siegel and Wagner 2022). For the null hypothesis ($H_0: \beta = 0$) to be rejected at the α = x significance level, the significance F needs to be less than x. If the null hypothesis is rejected at the α = x significance level, then the (1-x)*100% confidence interval for a parameter's coefficient will exclude zero, meaning that the direction of the impact a parameter has on the dependent variable (durability factor in this case) can be determined with (1-x)*100% certainty (Montgomery et al. 2021). In order to be able to reject the null hypothesis that states that the

Models with high adjusted R^2, low standard error, and low significance F values explain more of the variation in the durability factor with less error and greater certainty than those with low adjusted R^2, high standard errors, and high significance F values.

4.2.2. Logistic Regression Analysis

In addition to multivariable linear regression analysis, logistic regression analysis was also performed on the data obtained from literature. The factors analyzed using logistic regression analysis are shown in Table 4-2.

Table 4-2. Factors analyzed in logistic regression analysis.

Factor	Definition
w/cm	Water-to-cementing materials ratio
S_AEA_A	Use of synthetic as opposed to natural air-entraining admixtures
TAC (%)	Total air content
<x% TAC	Threshold total air content
>x SAM #	Threshold SAM number

Note: < and > denote a variable dependency on a threshold.

The research team decided to perform logistic regression analysis due its ability to determine the probability of concrete with a given set of properties to either pass or fail the freeze-thaw test (AASHTO T 161 2022). This is possible because in logistic regression analysis, the dependent variable (durability factor) is not a continuous variable, but rather a binary result, which in this case is either passing or failing the freeze-thaw test. This is useful because of the presence of a durability factor transition zone in the 2.5 to 3.5% total air content range. In this range, data from literature suggest that most concrete transitions from being non-freeze-thaw resistant (i.e. having a low durability factor) to being freeze-thaw resistant (having a high durability factor). In this study, the author considers concrete with a durability factor greater than or equal to 60 to have acceptable freeze-thaw resistance (Newlon 1978), while concrete with a durability factor greater than or equal to 80 is considered to have excellent freeze-thaw resistance (Obla et al. 2016). Logistic regression models for both thresholds were created and evaluated.

The analysis was performed using a Microsoft Excel add-in called RegressIt. Logistic regression works by transforming the original multivariable linear regression equation into the logit (logistic unit) scale to yield the natural log of the odds of being in one outcome category ($\hat{Y}$) versus the other outcome category (1 - $\hat{Y}$)(Stoltzfus 2011):

$$\ln\left(\hat{Y}/\left(1-\hat{Y}\right)\right) = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \ldots + \beta_n x_n \qquad \text{(Equation 2-2)}$$

For every set of concrete mixture data and test results, logistic regression analysis uses iterative cycles to identify the combination of variables and their coefficients that maximizes the likelihood of producing a given outcome (in this case, a durability factor of either 60 or 80 depending on the model). This iterative process is called maximum likelihood estimation (Stoltzfus 2011).

As in multivariable linear regression analysis, *p*-values and standardized coefficients are reported. Additionally, area under the receiver operating characteristic curve (AUC), Akaike information criterion (AIC), and maximum variance inflation factor (VIF) are also reported.

The AUC is used to evaluate the model’s ability to assign higher probabilities of an outcome (passing the freeze-thaw test) to the subgroup that develops the outcome than to the subgroup that does not develop that outcome (Hosmer et al. 2013). The AUC has a value between 0 and 1 with the following general guidelines indicating model performance: an AUC of 0.5 suggests no discrimination, while values between 0.7 and 0.8 are considered acceptable, values between 0.8 and 0.9 indicate excellent discrimination, and any value exceeding 0.9 is considered outstanding (Hosmer et al. 2013).

Like adjusted R^2, the AIC is used to compare models with different numbers of dependent variables. Models that include independent variables that are not statistically significant have higher AIC values than those that do not have statistically insignificant independent variables. There is no standard for what is considered an acceptable AIC, but rather models with lower values of AIC are preferred to models with higher AIC values (Hosmer et al. 2013).

The maximum VIF is used to indicate the maximum degree of multicollinearity between a set of independent variables. A set of independent variables will have a high maximum VIF if at least two variables are highly correlated with each other. This can cause the model to struggle to determine which variable is causing the change in the dependent variable, meaning that when a high degree of multicollinearity is present, coefficients may be poorly estimated (Montgomery et al. 2021). A general VIF threshold for when multicollinearity is considered problematic is 10, meaning that when the VIF is 10 or greater, there is a significant degree of multicollinearity in the model (Jacob and Varadharajan 2024). If there is no correlation between independent variables, the VIF will equal its minimum possible value of 1.

4.3 Data Collection

A total of 391 sets of concrete mixture data including w/cm ratios, type of air-entraining admixture, and type of water-reducer were collected from six studies which are shown in Table

4-3. Additionally, fresh total air content, SAM number, spacing factor, and durability factor data belonging to these concrete mixtures were also collected to be analyzed.

Table 4-3. Sources of Concrete Mixture and Testing Data Analyzed in this Study.

Number of Data Sets Contributed	Source
125	(W. A. Cordon and Merrill 1961)
149	(Janssen and Snyder 1994)
68	(Ley et al. 2017)
18	(Sutter 2007)
22	(Tanesi and Meininger 2006)
9	(Tanesi et al. 2016)

4.4 Minimum Total Air Content Optimization for a Target Durability Factor of 60 or Greater

As discussed in Section 4.2, concrete mixture and testing data were collected from literature. Figure 4-1 shows all 391 durability factor versus total air content results collected from literature. Also shown are the w/cm of each concrete mixture, a vertical line showing the current ALDOT minimum required total air content of 2.5%, and a horizontal line showing an acceptable durability factor of 60.

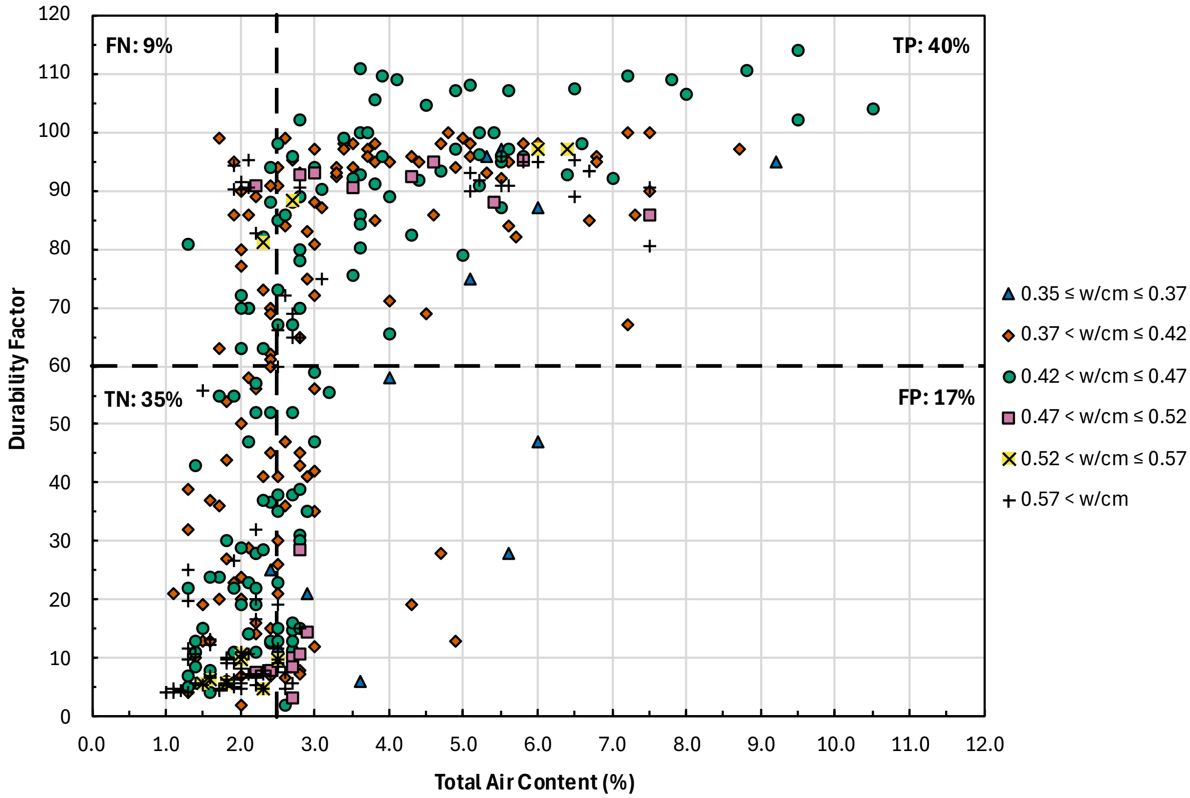


Figure 4-1. Durability Factor versus Total Air Content (%) data obtained from literature (n = 391). The vertical line shows the current ALDOT minimum permitted total air content of 2.5%, and the horizontal line shows an acceptable durability factor of 60.

Figure 4-1 shows an S-shaped curve in which most concrete mixtures transition from being non-durable in the 1.0 to 2.0% total air content range to being durable when their total air content is greater than 3.5%. This finding is supported by Tanesi and Meininger (2006) who found that concrete mixtures with fresh total air contents of 3.5 and 4.5% present similar freeze-thaw resistance, with them lasting 300 cycles in AASHTO T 161 (2022) testing and having durability factors that are greater than 80. This pattern is especially true for concrete mixtures with a w/cm greater than 0.42 as every mixture in this category with a total air content greater than 3.5% has an acceptable or excellent durability factor.

The pattern is also largely true for concrete mixtures with w/cm ≤ 0.42 but with seven exceptions being observed instead of one. These exceptions are likely caused by the presence of PC HRWR admixtures in the w/cm = 0.35 and 0.40 concrete mixtures which may negatively affect the air-void system of the concrete. It is likely that the air-void systems of the concrete mixtures included in this study made with PC HRWR are coarser than those made without PC HRWR as was sometimes the case for Freeman (2012). This means that the hardened cement paste of mixtures with PC HRWR admixture likely contains air voids that are large and spaced far apart, thus resulting in their air-void systems having spacing factors and specific surfaces that do not meet the recommended maximum spacing factor of 0.008 inches and the minimum specific surface of 600 $in.^2/in.^3$ for freeze-thaw durability defined in ACI 201.2. This theory is supported by research from Freeman (2012) that showed that at a given total air content, mixtures that contained PC HRWR admixtures had larger spacing factors than mixtures that did not contain PC HRWR admixture. Additionally, of five concrete mixtures with total air contents in the 4.5 to 5.7% range that were made with five different PC HRWR admixtures, only three passed the freeze-thaw test (Freeman 2012). Freeman (2012) attributes this variability in performance to the differing chemical formulations of the five admixtures. This is further supported by Xiang et al. (2022) who states that the air-void system is affected by properties of the PC HRWR admixture such as its acid-to-ether ratio, its sulfonic acid group, and its ester group along with the type of air-entraining admixture used alongside it.

Results in Figure 4-1 were classified according to Table 4-4 as being true positive (TP), true negative (TN), false positive (FP), or false negative (FN) depending on their durability factor and total air content. The percentage of concrete that fell into each category is also shown in Figure 4-1.

Table 4-4. Classification Categories for durability factor versus total air content data.

Total Air Content	Measured Performance: Acceptable Durability (DF ≥ 60)	Measured Performance: Poor Durability (DF < 60)
≥ 2.5%	True Positive (TP)	False Positive (FP)
< 2.5%	False Negative (FN)	True Negative (TN)

The practical implications and field outcomes associated with each classification category are defined as follows:

1. True positive: The specification requirement correctly identifies durable concrete. The mixture is accepted and placed in the field and should exhibit acceptable long-term freeze-thaw resistance.
2. True negative: The specification requirement correctly identifies potentially low-durability concrete. The deficient mixture is rejected at the jobsite, thereby preventing premature freeze-thaw deterioration in the field.
3. False positive: The specification requirement incorrectly identifies potentially low-durability concrete as acceptably durable. This low-durability concrete is subsequently placed in the field and prematurely deteriorates. This category represents an agency (consumer) risk borne by ALDOT.
4. False negative: The specification requirement incorrectly identifies potentially acceptably durable concrete as having low durability. Consequently, a mixture that

should be freeze-thaw resistant is rejected. This category represents a risk borne by the contractor and thus the concrete supplier.

The process of categorizing the results based on a durability factor threshold of 60 and a total air content threshold was repeated for threshold total air contents of 3.0, 3.5, and 4.0%. The percentages of results that fell into the false positive and false negative categories are shown in Figure 4-2 and Figure 4-3.

The focus is on the amount of false positive and false negative results, because the remaining percentage of results is correctly categorized as either true positive or true negative. Figure 4-2 shows that the percentage of false positive results decreases from 17 to 4% when the minimum required total air content increases from 2.5 to 3.0%. There is a further marginal decrease in false positive results (from 4 to 2%) when the total air content threshold is raised from 3.0 to 3.5% and no decrease in false positive results when the total air content threshold is increased from 3.5 to 4.0%.

Figure 4-3 shows that as the minimum required total air content increases, so does the percentage of false negative results. The most substantial increase in the percentage of false negative results is 8%, which corresponds to when the minimum total air content threshold is raised from 2.5 to 3.0%. Increasing the total air content threshold from 3.0 to 3.5% and from 3.5 to 4.0% each result in an increase of the percentage of false positive results of 4%.

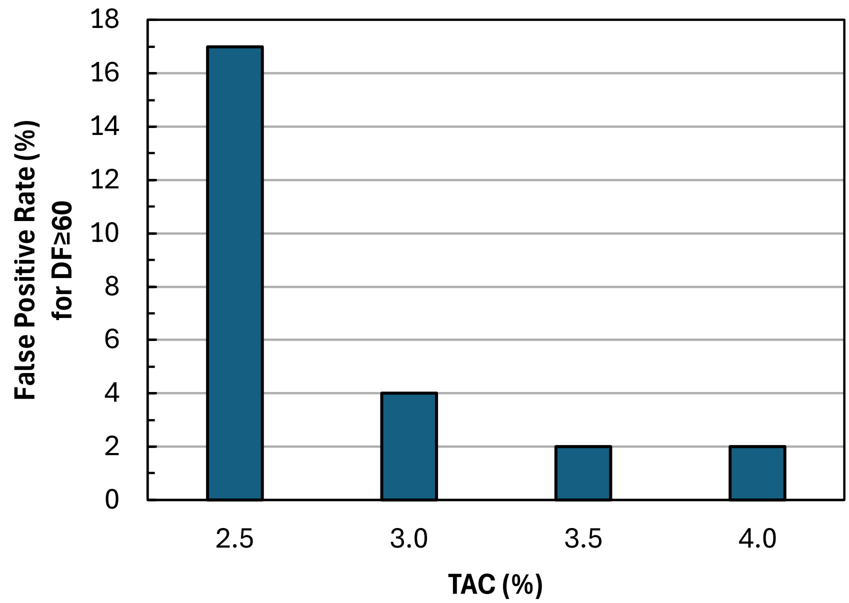


Figure 4-2. False positive rates for a durability factor threshold of 60 and total air contents of 2.5, 3.0, 3.5, and 4.0%.

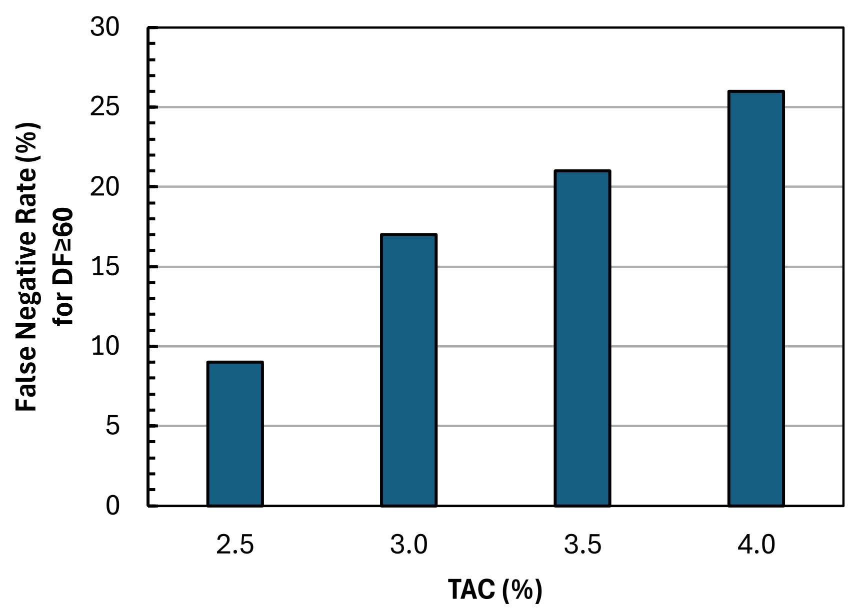


Figure 4-3. False negative rates for a durability factor threshold of 60 and total air contents of 2.5, 3.0, 3.5, and 4.0%.

The false positive results indicate that there is potentially a considerable improvement in concrete freeze-thaw performance that ALDOT can achieve by changing the minimum required total air content from 2.5 to 3.5%. This decreases the percentage of false positive results from 17 to 2%, meaning that in the long term the percentage of potentially non-durable concrete that will be accepted and placed in the field will be substantially lower compared to what it would be if the minimum total air content remains at 2.5%. This could result in substantial financial savings for ALDOT since structures made with freeze-thaw resistant concrete should have a substantially longer service life than structures made without freeze-thaw resistant concrete when exposed to moisture in a severe freeze-thaw environment. Moreover, because structures should have longer service lives, reduced maintenance activities will be necessary which will result in fewer lane closures and less construction-induced congestion. A minimum required total air content of 4.0% is not recommended since changing the total air content from 3.5 to 4.0% results in no change in false positive results and an increase of 4% in false negative results. The downside of increasing the minimum required total air content from 2.5 to 3.5% is that the percentage of potentially durable concrete that will be rejected will increase from 9 to 21%. Additionally, concrete producers may need to use increased dosages of air-entraining admixtures and implement improved quality control measures to ensure that they produce concrete mixtures with total air contents of at least 3.5%. Higher total air content will also require a decrease in w/cm to achieve the required compressive strength.

4.5 Minimum Total Air Content Optimization for a Target Durability Factor of 80 or Greater

The process of categorizing durability factor versus total air content results into categories was repeated for an excellent durability factor of 80 using the same total air content thresholds.

An excellent durability factor of 80 is not recommended for ALDOT use but might be applicable to locations subjected to more extreme freeze-thaw exposure conditions. Figure 4-4 and Figure 4-5 show the percentages of results that are classified as being false positive and false negative, respectively, for total air content thresholds of 2.5, 3.0, 3.5, and 4.0%.

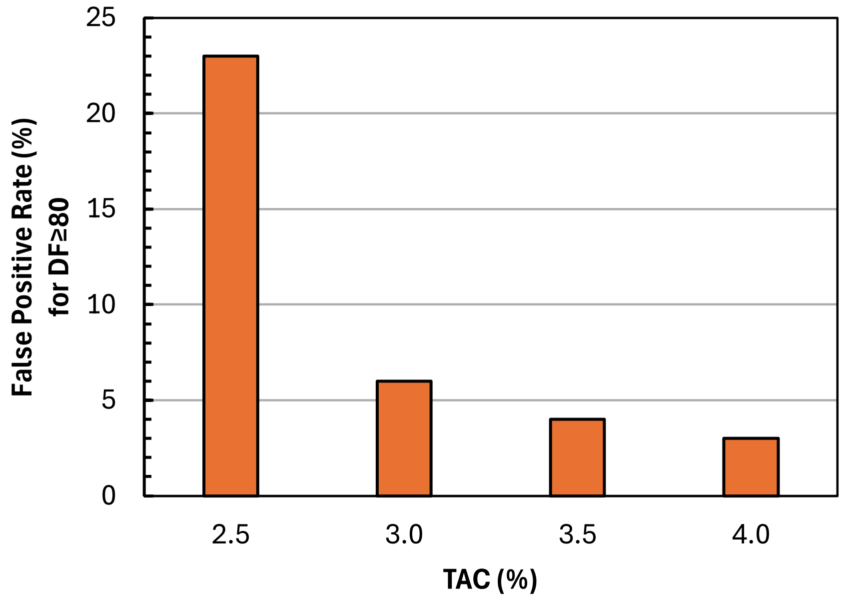


Figure 4-4. False positive rates for a durability factor threshold of 80 and total air contents of 2.5, 3.0, 3.5, and 4.0%.

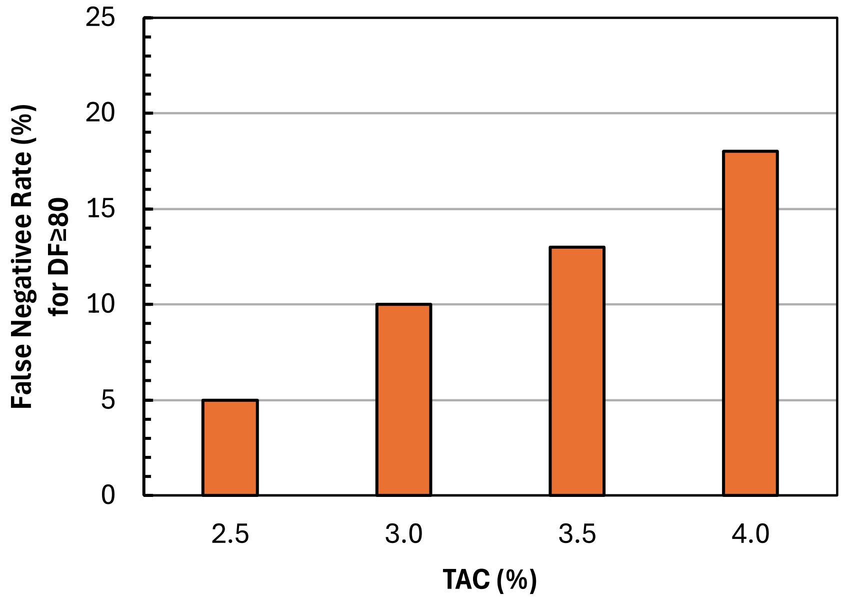


Figure 4-5. False negative rates for a durability factor threshold of 80 and total air contents of 2.5, 3.0, 3.5, and 4.0%.

Figure 4-4 shows that as the total air content threshold is increased from 2.5 to 3.5%, the percentage of false positive results decreases significantly from 23 to 4%. A marginal decrease of 1% in the percentage of false positive results is obtained by further raising the total air content threshold to 4.0%. Conversely, raising the total air content threshold from 2.5 to 3.5% raises the false negative rate from 5 to 13%. If the total air content threshold is raised to 4.0%, this would result in a false negative rate of 18%, an increase of 5%. Given these results, for a target durability factor of 80 or greater, the optimum minimum total air content threshold is 3.5%. If implemented, on average this would potentially result in only 4% of concrete structures placed having a durability factor less than 80 while also potentially limiting the percentage of freeze-thaw resistant concrete mixtures that are rejected to 13%.

4.6 Comparison of False Positive and False Negative Rates for Target Durability Factors of 60 and 80

This subsection compares the results presented in the previous two subsections so that the reader can easily compare the false positive and false negative rates for durability factor thresholds of 60 and 80. Figure 4-6 and Figure 4-7 show the false positive and false negative rates, respectively, for both durability factor thresholds and total air contents of 2.5, 3.0, 3.5, and 4.0%.

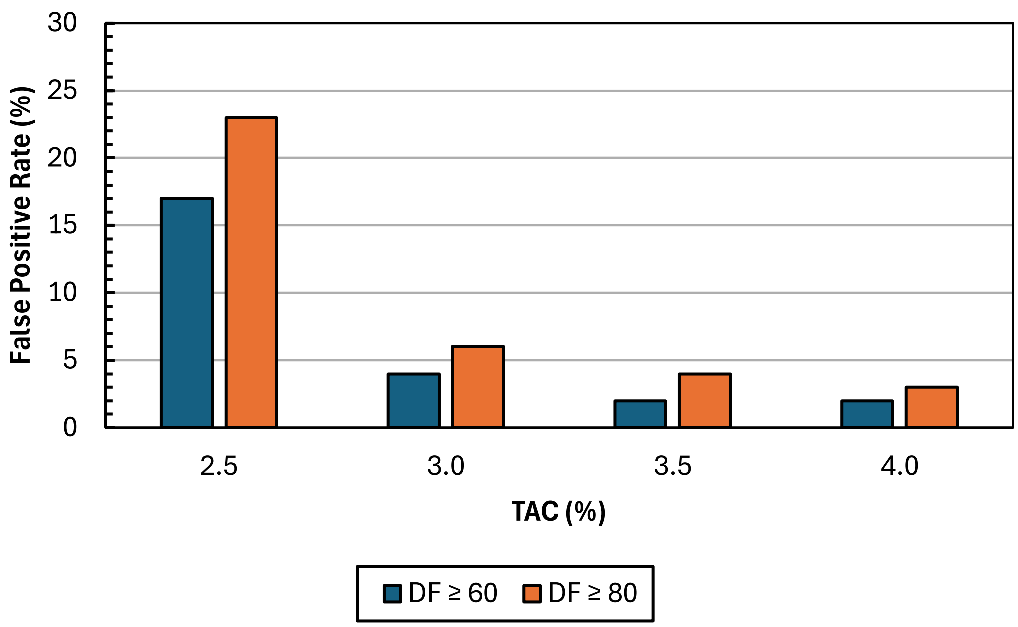


Figure 4-6. False positive rates for durability factor thresholds of 60 and 80 and total air contents of 2.5, 3.0, 3.5, and 4.0%.

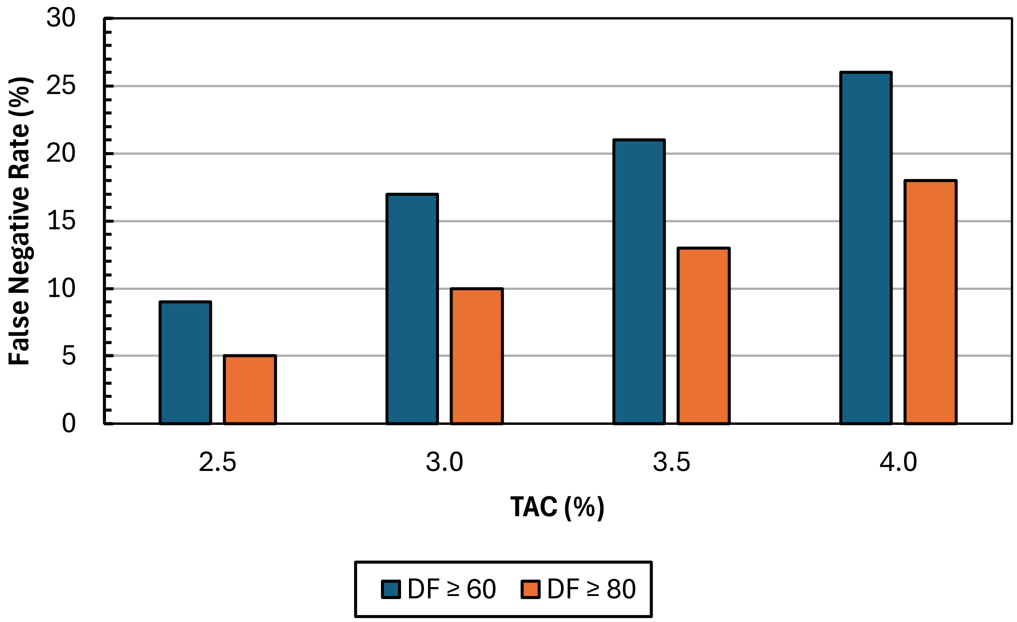


Figure 4-7. False negative rates for durability factor thresholds of 60 and 80 and total air contents of 2.5, 3.0, 3.5, and 4.0%.

False positive rates are similar regardless of whether a durability factor threshold of 60 or 80 is specified with the maximum difference being 6% at a total air content of 2.5%. At the recommended 3.5% total air content, the difference narrows to just 2%, with the false positive rates being 2 and 4% for durability factor thresholds of 60 and 80, respectively. Additionally, across all total air content thresholds, the false positive rate remains marginally higher when utilizing the higher durability factor threshold of 80.

Conversely, Figure 4-7 shows that for both durability factor thresholds, the false negative rate increases monotonically with the total air content threshold. The percentages of false negative results are consistently higher for the durability factor threshold of 60 than for the durability factor threshold of 80. From a practical standpoint, this indicates that if ALDOT establishes a durability factor threshold of 60 as acceptable, a greater number of freeze-thaw resistant concrete mixtures will be falsely classified as non-durable and therefore rejected compared to if a more conservative threshold of 80 is used.

Regardless of which durability factor threshold is used, the optimum threshold total air content is 3.5%. This is because increasing the total air content threshold from 2.5 to 3.5% drastically reduces the false positive rate and therefore the amount of non-durable concrete that is accepted and placed. Furthermore, increasing the threshold to 4.0% yields almost no benefit to ALDOT while increasing the amount of durable concrete that is rejected in the field, a downside for contractors. Additionally, using 4.0% instead of 3.5% will require higher cementitious materials contents which is neither cost effective nor sustainable. Given this information, the 3.5% total air content threshold is the optimum compromise between ALDOT and contractors.

4.7 Relationships between Total Air Content, SAM Number, Spacing Factor, and Durability Factor

To better understand the relationships between the total air content, SAM number, spacing factor, and durability factor, the process of sorting results into quadrants described in Section 4.3 was repeated for different parameters. First, the relationship between two predictors of durability, total air content and spacing factor, was investigated using the optimized minimum total air content of 3.5% and the ACI 201.2 (2023) recommended maximum spacing factor of 0.008 inches to ensure adequate freeze-thaw durability (ACI 201.2 2023). The spacing factor versus total air content results and classifications are shown in Figure 4-8. Figure 4-8 shows that whether the spacing factor is greater than or less than 0.008 inches can be correctly predicted

77% of the time with a false positive rate of 20% based on whether the total air content is greater or less than 3.5%.

Next, the relationship between the SAM number and the spacing factor was investigated using the conservative maximum SAM number threshold of 0.20 recommended by Ley et al. (2017) and a spacing factor of 0.008 inches. The spacing factor versus SAM number results and classifications are shown in Figure 4-9. Figure 4-9 shows that the spacing factor can be correctly predicted using the SAM number 89% of the time with a false positive rate of 11%, an improvement in accuracy compared to predictions made using the total air content. Therefore, the data collected from literature in this study suggest that the SAM number is a better indicator of a concrete mixture's spacing factor than when using the concrete mixture's total air content.

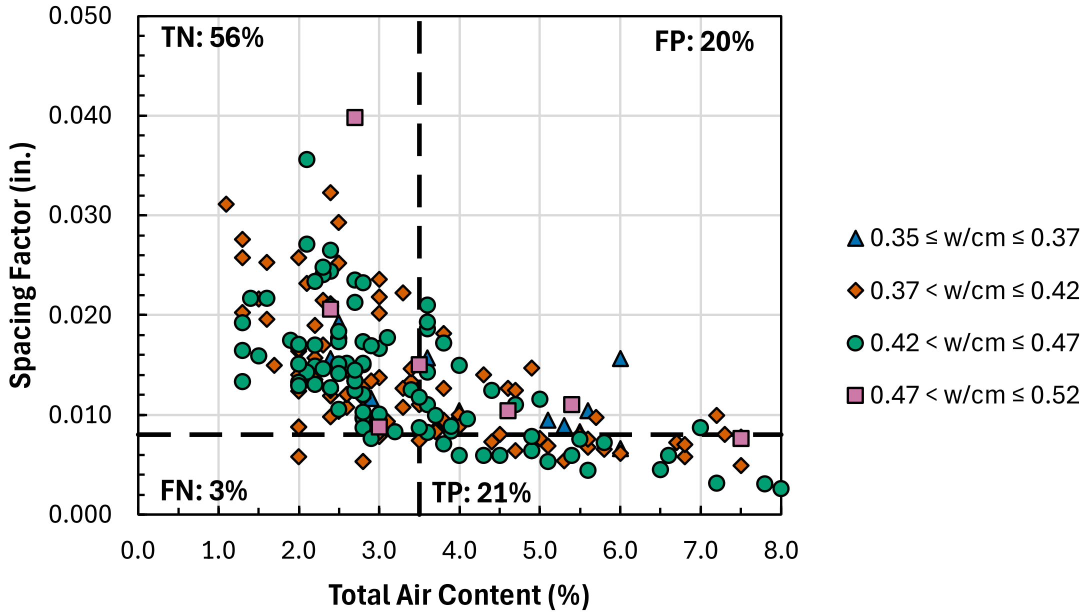


Figure 4-8. Spacing Factor (in.) versus Total Air Content (%) data obtained from literature (n = 209). The vertical line is the optimized total air content of 3.5%, and the horizontal line is the ACI 201.2 (2023) recommended maximum spacing factor of 0.008 in.

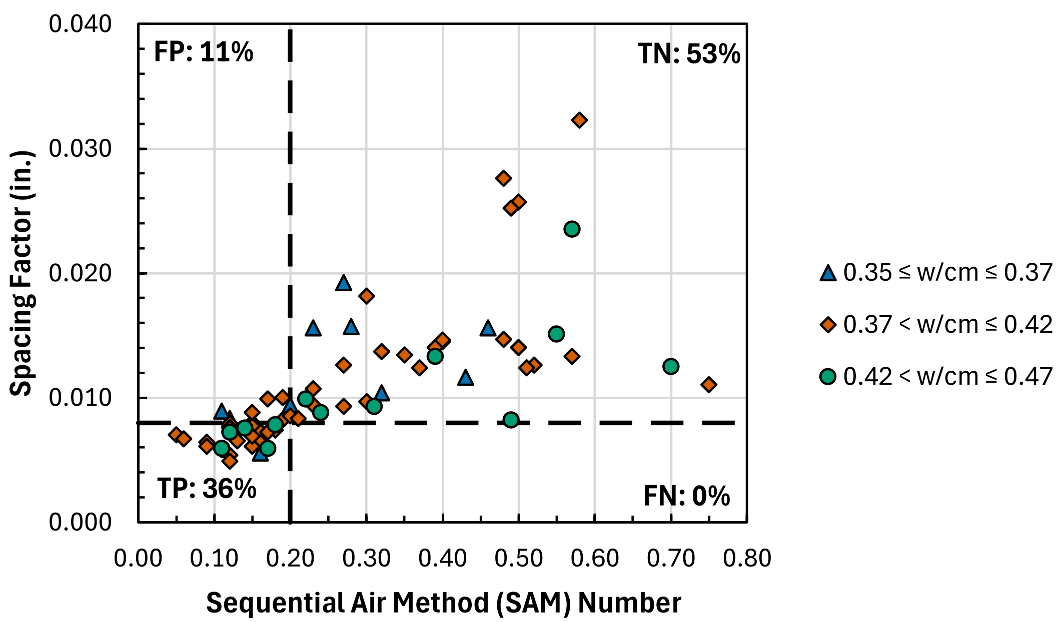


Figure 4-9. Spacing Factor (in.) versus SAM Number data collected from literature (n = 70). The vertical line is the recommended maximum SAM number of 0.20, and the horizontal line is the ACI 201.2 (2023) recommended maximum spacing factor of 0.008 in.

While the spacing factor is often regarded as the best predictor of a concrete mixture's freeze-thaw resistance due to its ability to provide an indication of the distribution and spacing of air voids in the hardened concrete, the research team was interested in knowing whether the spacing factor, SAM number, or total air content best separates concrete mixtures passing and failing AASHTO T 161 (2022). Figure 4-10 shows durability factor versus spacing factor results and classifications based on a spacing factor threshold of 0.008 inches and an acceptable durability factor of 60.

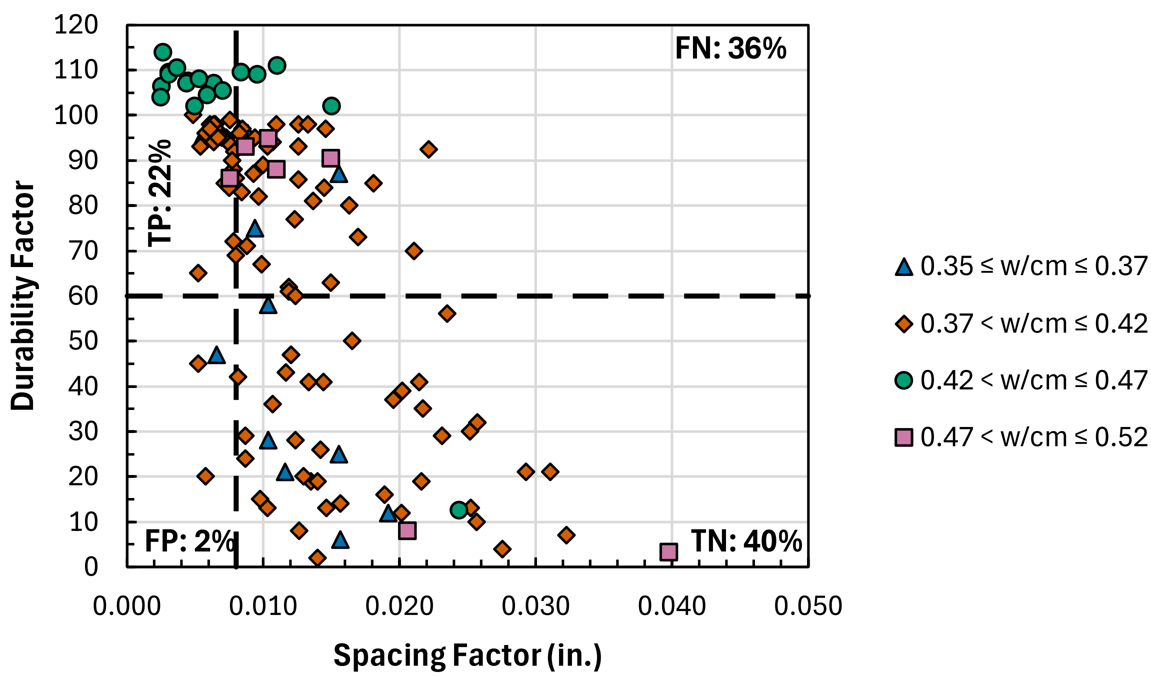


Figure 4-10. Durability Factor versus Spacing Factor (in.) (n = 209). The vertical line shows the ACI 201.2 (2023) recommended maximum spacing factor of 0.008 in., and the horizontal line shows an acceptable durability factor of 60.

Figure 4-11 shows durability factor versus SAM number results and classifications based on a SAM number of 0.20 and an acceptable durability factor of 60.

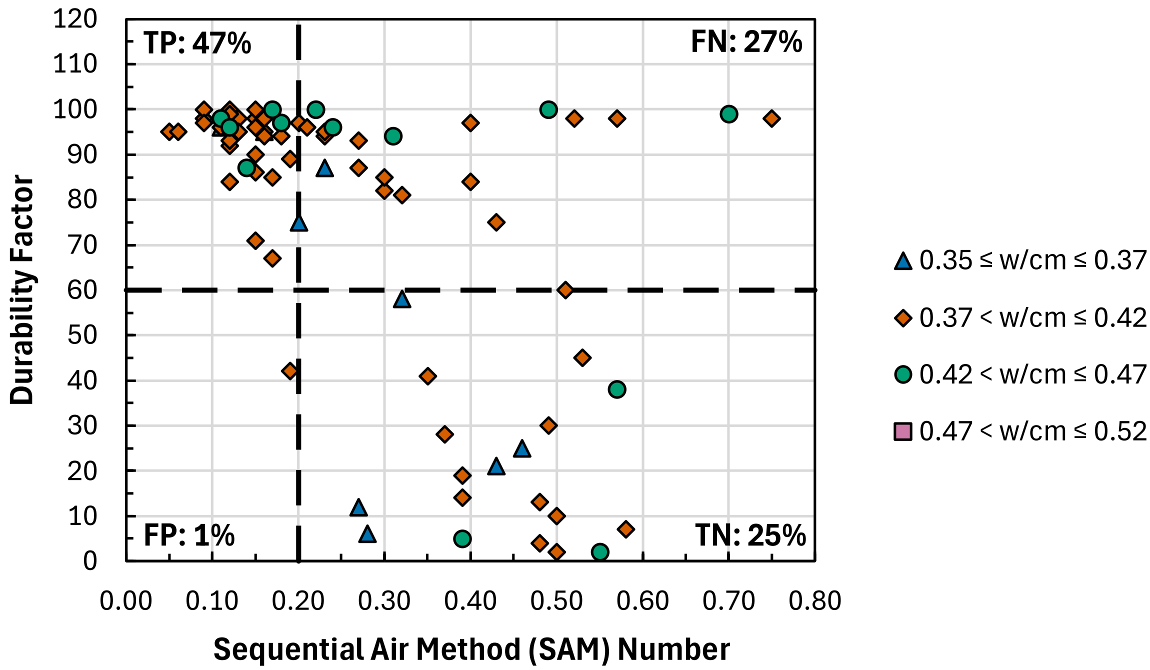


Figure 4-11. Durability Factor versus SAM Number (n = 77). The vertical line shows the recommended maximum SAM number of 0.20, and the horizontal line shows an acceptable durability factor of 60.

Figure 4-12 shows durability factor versus total air content results and classifications based on a SAM number of 0.20 and an acceptable durability factor of 60.

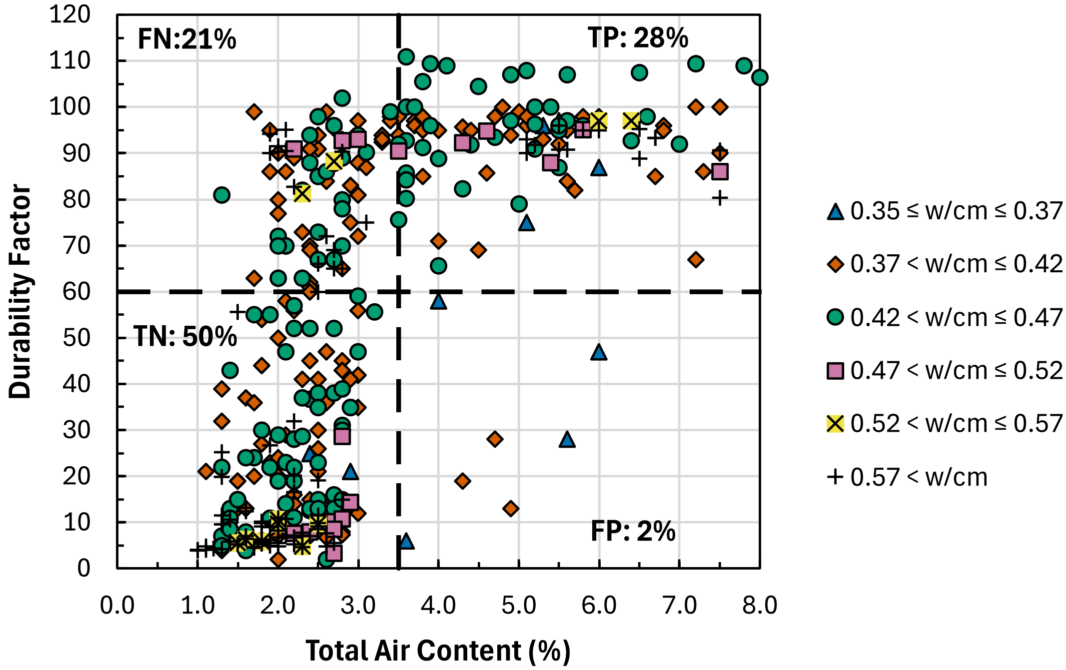


Figure 4-12. Durability Factor versus Total Air Content (%) (n = 391). The vertical line shows the optimized minimum total air content of 3.5%, and the horizontal line shows an acceptable durability factor of 60.

To make comparisons easier between the spacing factor, SAM number, and total air content predictors, categorization analysis results show on Figure 4-10, Figure 4-11, and Figure 4-12 are summarized in Table 4-5. The analysis reveals that among the three thresholds used, the total air content correctly predicts whether a concrete mixture will have a durability factor greater than or less than 60, 77% of the time compared to only 62% and 71% of the time for the spacing factor and SAM number, respectively. When evaluating error rates, all three indicators produce remarkably low and uniform false positive rates of only 1 to 2%. This indicates that regardless of the chosen indicator, only a negligible fraction of mixtures will be falsely predicted as durable when they are actually probably prone to freeze-thaw deterioration. While eliminating all non-durable mixtures is ideal, further tightening the thresholds described in this section to further reduce the risk of false positive results would cause a substantial increase in false negatives, resulting in the excessive rejection of potentially acceptable concrete mixtures in the field.

Table 4-5. Results of Categorization Analysis.

Categorization of Durability Factor >= 60 by Spacing Factor <= 0.008 in.						
	TP	**TN**	**FP**	**FN**	**Correct**	**Total**
Observations (n)	45	84	4	76	129	209
Percent	22	40	2	36	62	
Categorization of Durability Factor >= 60 by SAM Number <= 0.20						
	TP	**TN**	**FP**	**FN**	**Correct**	**Total**
Observations (n)	36	19	1	21	55	77
Percent	47	25	1	27	71	
Categorization of Durability Factor >= 60 by Total Air Content (%) >= 3.5%						
	TP	**TN**	**FP**	**FN**	**Correct**	**Total**
Observations (n)	108	194	7	82	302	391
Percent	28	50	2	21	77	

Note: TP = True Positive, TN = True Negative, FP = False Positive, FN = False Negative

4.8 Multivariable Linear Regression Analysis

Multivariable linear regression (MVLR) analysis, as described in Section 4.2.1, was performed to quantify the relative importance of each variable on the concrete mixture's freeze-thaw resistance as tested with AASHTO T 161 (2022). All variables included in this section are defined in Section 4.2.1. Twenty models were created that examined the statistical significance and impact of each variable. Only models in which all variables have a *p*-value less than 0.01 (α = 0.01 significance level) are reported in this section. This corresponds with a 99% confidence interval, meaning that if the null hypothesis ($H_0 \colon \beta = 0$) is rejected at the α = 0.01 significance level, the 99% confidence interval will exclude zero. If the 99% confidence interval for a parameter's coefficient excludes zero, then the direction of the impact a parameter has on the dependent variable (durability factor in this case) can be determined with 99% certainty

(Montgomery et al. 2021). Other models not included in this section are included in Appendix A. Table 4-6 shows the average and standard deviation of total air content (%), w/cm, spacing factor (SF), SAM number, and durability factor (DF) data collected from literature.

Table 4-6. Average and standard deviation of total air content (TAC), w/cm, spacing factor (SF), SAM number, and durability factor (DF) data collected from literature.

Value	TAC (%)	w/cm	SF (in.)	SAM Number	DF
Average	3.6	0.42	0.0132	0.28	63.27
Standard Deviation	1.8	0.03	0.0065	0.17	33.22

4.8.1. Influence of Total Air Content and w/cm

Table 4-7 shows the analysis results for models MVLR 1 through MVLR 3 which examine the significance and impact of varying threshold total air contents (<x% TAC), w/cm, and total air content (TAC (%)).

Table 4-7. Multivariable Linear Regression (MVLR) Analysis Results for Models MVLR 1 through MVLR 3.

Model	**MVLR 1**	**MVLR 2**	**MVLR 3**
TAC (%) Threshold	**2.5**	**3.0**	**3.5**
Adjusted R^2	0.45	0.48	0.45
Standard Error	0.74	0.72	0.74
Significance F	6.68E-50	5.05E-56	1.19E-50
Variable	***p*-value**		
<x% TAC	1.54E-04	6.86E-11	2.49E-05
w/cm	2.55E-03	4.53E-03	5.29E-04
TAC (%)	2.46E-21	2.16E-06	2.46E-07
Variable	***t*-statistic**		
<x% TAC	-3.82	-6.71	-4.27
w/cm	-3.04	-2.86	-3.50
TAC (%)	10.07	4.81	5.25
Variable	**β Coefficient**		
<x% TAC	-0.38	-0.86	-0.65
w/cm	-0.12	-0.11	-0.13
TAC (%)	0.50	0.29	0.37

The adjusted R^2 values indicate that model MVLR 2, with a total air content threshold of 3.0%, explains the greatest percentage (48%) of the variance of the durability factor results. It also has the lowest standard error of regression and the lowest significance F, which indicates that there is less error and a greater certainty that the set of variables predict the durability factor in this model than in models MVLR 1 and MVLR 3. This suggests that the most statistically significant total air content threshold for predicting the durability factor is actually 3.0%, not 3.5%; however, the difference in results is not much. This agrees with Figure 4-1 which shows a large increase in the number of concrete mixtures with durability factors greater than or equal to 60 at the 3.0% total air content threshold.

The *p*-value for each variable in each model is less than 0.01 which indicates that there is a high degree of certainty that each variable provides statistically significant variance to the model, or in practical terms, influences the durability factor. Regardless of the model, the threshold total air content coefficients indicate that if a concrete mixture's total air content is below the model's threshold total air content, it will have a durability factor that is substantially less than a concrete mixture that has a total air content that is greater than or equal to the model's threshold. In the case of Model 10, the β coefficient of -0.86 suggests that if a concrete mixture has a total air content that is less than 3.0%, its expected durability factor will be 0.86 standard deviations (or 28.6) lower than a concrete mixture with a total air content of 3.0% or greater. The magnitudes of the β coefficients of the w/cm variable are roughly 1/8 to 1/3 those of the threshold total air content and 1/4 to 2/5 those of the total air content variables. This suggests that w/cm has much less influence on the durability factor than the total air content does. This is supported by Tanesi and Meininger (2006) who found that w/cm did not appear to play a significant role in concrete's freeze-thaw resistance with it having a correlation with the durability factor of just 0.04. By contrast, they found that the correlation between durability factor and total air content was 0.78, thus indicating that total air content has a much more significant impact on a concrete mixture's freeze-thaw resistance than the w/cm. Furthermore, Freeman (2012) found that there was no difference in the minimum total air content required to produce freeze-thaw resistant concrete for concrete mixtures with different w/cm.

The negative sign of the w/cm variable indicates that as the w/cm increases, durability is expected to decrease. One reason for this is that mixtures with higher w/cm have more freezable water in their paste structure that is vulnerable to expansion upon freezing (ACI 201.2

2023). This expansion induces tensile stress in the paste. When this stress exceeds the tensile strength of the paste, cracking occurs that allows for external water ingress. Another reason why the w/cm affects freeze-thaw resistance is that as the w/cm increases, so does the porosity and the permeability (Goto and Roy 1981). This is further supported by Kim et al. (2014) who found that increasing the w/cm of mortar with a 5.2% total air content from 0.45 to 0.60 increased the porosity by 50%, the chloride diffusion coefficient by 57%, the sorptivity by 159%, and the moisture diffusion coefficient by 166%. This increased permeability allows for greater and faster water ingress into the cement matrix. As a result, mixtures with higher w/cm will become critically saturated sooner than those with low w/cm, thus allowing more damage to occur sooner in mixtures with high w/cm compared to those with low w/cm. As mentioned above, however, the impact of the increased freezable water content, increased porosity, and increased permeability in concrete mixtures with high w/cm on the concrete's freeze-thaw resistance is negligible compared to the impact of the total air content. Additionally, if a high w/cm mixture has a better air-void system than a low w/cm mixture, the coefficients in Table 4-7 suggest that the mixture with the high w/cm and better air-void system will have better freeze-thaw durability.

The magnitudes of the coefficients of the TAC (%) variable vary depending on the model but are always positive and greater than those of the w/cm variable. When the total air content is less than 2.5%, each standard deviation increase in total air content (1.8%) is expected to increase the durability factor by 0.50 standard deviations (16.61). However, when the total air content is greater than 3.0 and 3.5%, this 1.8% total air content increase is expected to increase the durability factor by only 0.29 and 0.37 standard deviations, or by 9.64 and 12.29, respectively. This finding is supported by Tanesi and Meininger (2006) who found that concrete mixtures with total air contents of 3.5 and 4.5% have similar freeze-thaw resistance, thus indicating that for each increase in total air content above 3.5%, there is a marginal impact on freeze-thaw resistance. However, it should be noted that Tanesi and Meininger's research did not include PC HRWR admixtures, and that as discussed in Section 4.3, more entrained air might be needed in concrete mixtures containing PC HRWR admixtures.

4.8.2. Influence of Spacing Factor and w/cm

Table 4-8 shows multivariable linear regression analysis results for models MVLR 4, MVLR 5, and MVLR 6 which evaluate the significance and impact of varying w/cm and spacing factor [SF (in.)] in the case of model MVLR 4 and the impact of varying a threshold spacing factor (>x in. SF), w/cm, and spacing factor [SF (in.)] in the case of models MVLR 5 and MVLR 6. The threshold spacing factor was varied to examine the adequacy of the ACI 201.2 (2023) recommended spacing factor of 0.008 inches, as studies have found that some mixtures with spacing factors greater than 0.008 inches can perform well in AASHTO T 161 (2022) testing (Felice et al. 2014; Tanesi et al. 2016).

Table 4-8. Multivariable Linear Regression Analysis Results for Models MVLR 4, MVLR 5, and MVLR 6.

Model	**MVLR 4**	**MVLR 5**	**MVLR 6**
SF (in.) Threshold	**--**	**0.010**	**0.012**
Adjusted R^2	0.37	0.39	0.39
Standard Error	0.80	0.78	0.78
Significance F	1.76E-21	2.39E-22	3.23E-22
Variable	**P-value**		
>x in. SF	--	3.75E-03	5.23E-03
w/cm	1.00E-02	6.43E-03	5.73E-03
SF (in.)	3.32E-22	4.27E-08	8.89E-07
Variable	***t*-statistic**		
>x in. SF	--	-2.93	-2.82
w/cm	2.60	2.75	2.79
SF (in.)	-10.92	-5.69	-5.07
Variable	**B Coefficient**		
>x in. SF	--	-0.47	-0.47
w/cm	0.14	0.15	0.15
SF (in.)	-0.61	-0.44	-0.43

The adjusted R^2 results obtained from using the spacing factor as a predictor of durability (0.37 to 0.39) are lower than those obtained from using the total air content as a predictor of durability (0.45 to 0.48). This indicates that less of the variation is explained when using the spacing factor than the total air content. Additionally, the standard errors of regression are higher, and the significance F values are lower, thus indicating more model error and less certainty that the group of variables in Table 4-8 explain the durability factor. This is consistent with the finding in Section 4.7 that the spacing factor correctly classifies into true positive and true negative only 62% of freeze-thaw testing results, while the total air content correctly classifies 77% of freeze-thaw testing results.

While the results for all three models are very similar, the adjusted R^2, standard error, and significance F are similar for models MVLR 5 and MVLR 6. This suggests that concrete mixtures with spacing factors of 0.010 and 0.012 inches perform very similarly when subjected to AASHTO T 161 (2022) testing. A threshold spacing factor of 0.008 inches was also evaluated but was found to not be statistically significant at the $\alpha = 0.01$ significance level with it having a *p*-value of 0.028. This is shown in model MVLR 20 included in Appendix A. A potential reason for this is that many concrete mixtures with spacing factors that are greater than 0.008 inches but less than or equal to 0.012 inches have similar durability factors as those with spacing factors of 0.008 inches or less. This finding is supported by results from Malhotra (1977) and Tanesi et al. 2016 (2016) who also found that some concrete mixtures that had spacing factors of approximately 0.010 inches had acceptable freeze-thaw resistance.

As expected, the β coefficients in Table 4-8 for the threshold spacing factor and spacing factor are approximately 3 to 4 times larger than those of the w/cm, thus indicating that the spacing factor has a larger influence on the durability factor than the w/cm. Directionally, the sign of the threshold spacing factor indicates that if a concrete mixture's spacing factor is greater than the threshold, its durability factor is expected to be 0.47 standard deviations (15.61) less than that of a concrete mixture with a spacing factor less than the threshold. The sign and magnitude of the spacing factor coefficient indicate that a one standard deviation increase in spacing factor (or 0.0065 inches) is expected to decrease the durability factor by 0.43 to 0.44 standard deviations (14.28 to 14.62) depending on the model.

The reason for the coefficients of the w/cm factor being positive is not known. Based on the positive benefits of lowering the w/cm on the concrete mixture's porosity and permeability and the results discussed in Section 4.8.1, it was expected that the w/cm variable in this analysis would have a negative coefficient. Regardless, the comparatively small magnitude of coefficients of the w/cm variable in Models 9, 10, 11, 13, 19, and 20 suggest that w/cm is far less influential on a concrete mixture's durability than the air-void system.

4.8.3. Influence of Type of Air-Entraining Admixture and PC HRWR Admixture

The influence of the type of air-entraining admixture and PC HRWR admixtures on the durability factor were also evaluated and found to not be consistently significant to the $\alpha = 0.01$ level. In models MVLR 10 through MVLR 14, the inclusion of synthetic air-entraining admixture versus natural air-entraining admixtures was found to be statistically significant to the $\alpha = 0.05$ level or greater and to moderately improve concrete's freeze-thaw resistance. However, in models MVLR 8, MVLR 9, and MVLR 16 through MVLR 19, it was found to not be statistically significant and to have no impact on concrete's freeze-thaw resistance. Therefore, the results of the multivariable linear regression analysis are inconclusive with regards to the influence of synthetic air-entraining admixture versus natural air-entraining admixtures.

Other research from literature regarding the influence of the type of air-entraining admixture on concrete mixtures' air-void systems is also inconclusive. For instance, Freeman (2012) tested the stability of the air-void system of concrete mixtures made using vinsol resin, wood rosin, and synthetic air-entraining admixtures. Freeman (2012) found that the type of air-entraining admixture did not impact the volume of air that escaped the cement paste over the course of two hours. He also found that the use of synthetic air-entraining admixture produced concrete with the lowest spacing factor and highest specific surface. The concrete mixture containing synthetic air-entraining admixture also had the smallest changes in the air-void system over sixty minutes despite its dosage being less than the dosages used for the vinsol resin and wood rosin admixtures. Tanesi and Meininger (2006) tested concrete mixtures made with vinsol resin and two synthetic air-entraining admixtures and found that the mixtures made with vinsol resin exhibited better freeze-thaw resistance despite having worse air-void systems. However, Felice, Freeman, and Ley (2014) found that regardless of the type of air-entraining admixture, for concrete mixtures with w/cm = 0.41 and 0.45 without water-reducing admixtures, as long as they had a total air content of at least 3.5% (corresponding to 11.0% air in the cement paste) and a spacing factor of 0.010 inches or less, they performed adequately in AASHTO T 161 (2022) testing.

The impact of the inclusion of polycarboxylate (PC) HRWR admixture on the concrete's freeze-thaw resistance was evaluated and found to be statistically significant to the $\alpha = 0.27$ significance level. This suggests that there is weak evidence that the inclusion of PC HRWR admixtures consistently increases or decreases the durability factor. This is evident in Figure 4-1 which shows that the durability factors of concrete mixtures with w/cm = 0.40 or less, most of which contain PC HRWR admixture, are scattered with some being greater than 60 and others being less than 60. This suggests that some concrete mixtures containing PC HRWR admixture may perform adequately while others may not. This is consistent with the findings of Freeman (2012) discussed in the literature review and Section 4.3 that found that some PC HRWR admixtures produce concrete mixtures with coarser air-void systems than others. Because the effect of PC HRWR admixtures is variable, the multivariable linear regression analysis did not find it to be statistically significant to the $\alpha = 0.01$ significance level.

4.9 Logistic Regression Analysis

Logistic regression (LR) analysis, as described in Section 4.2.2, was performed to quantify the relative importance of each variable on the concrete mixture's freeze-thaw resistance (durability factor). All variables and logistic regression analysis metrics included in this section are defined in Section 4.2.2. Logistic regression analysis is useful for agencies that wish to specify acceptable thresholds for total air content and/or SAM number since it treats each concrete mixture's durability factor as a binary quantity of 0 or 1 depending on whether it is less than or greater than the threshold durability factor used in the model. Twenty-six models were created that examined the statistical significance and impact of each variable examined. Only models in which all variables have a *p*-value less than 0.01 ($\alpha = 0.01$ significance level) that corresponds to a 99% confidence interval, in which zero is included from the range of possible values for β coefficients, are reported in this section. Other models not included in this section are included in Appendix A.

4.9.1. Influence of Total Air Content

Table 4-9 shows the analysis results for models LR 1 through LR 4 which examine the influence of whether a concrete mixture has a total air content that is greater or less than the threshold specified for the model for a target durability factor of 60 or greater. Table 4-10 shows the analysis results for models LR 5 through LR 8 which examine the influence of whether a concrete mixture has a total air content that is greater or less than the threshold specified for the model for a target durability factor of 80 or greater.

Table 4-9. Results of Logistic Regression (LR) Analysis for Models LR 1 through LR 4.

Model	**LR 1**	**LR 2**	**LR 3**	**LR 4**
>=x DF Threshold	**60**	**60**	**60**	**60**
<x% TAC Threshold	**2.5**	**3.0**	**3.5**	**4.0**
Area Under ROC Curve	0.74	0.79	0.76	0.71
AIC	447.3	391.5	396.0	435.2
Maximum VIF	1.00	1.00	1.00	1.00
Variable	***p*-value**			
<x% TAC	0.00E+00	0.00E+00	0.00E+00	7.70E-14
Variable	**β Coefficient**			
<x% TAC	-0.60	-0.83	-0.90	-0.77

Table 4-10. Results of Logistic Regression (LR) Analysis for Models LR 5 through LR 8.

Model	**LR 5**	**LR 6**	**LR 7**	**LR 8**
>=x DF Threshold	**80**	**80**	**80**	**80**
<x% TAC Threshold	**2.5**	**3.0**	**3.5**	**4.0**
Area Under ROC Curve	0.75	0.82	0.80	0.74
AIC	428.3	349.2	359.2	407.3
Maximum VIF	1.00	1.00	1.00	1.00
Variable	***p*-value**			
<x% TAC	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Variable	**β Coefficient**			
<x% TAC	-0.65	-0.86	-0.86	-0.71

The area under the ROC curve values in Table 4-9 indicate that between models LR 1 through LR 4, model LR 2 is the best at assigning higher probabilities of the mixtures having a durability factor of at least 60 to the mixtures that actually do have a durability factor of 60 or greater than it does to the mixtures that do not have a durability factor of 60 or greater. This, along with the β coefficient of -0.83, suggests that there is a significant decrease in the odds of the durability factor being greater than or equal to the threshold of 60 when the concrete mixture's total air content is less than 3.0%. This supports the finding in Section 4.8.1 that the best total air content threshold for predicting durability is 3.0%. To further support this, between models LR 1 through LR 4, model LR 2 has the lowest AIC and no multicollinearity, indicated by a maximum VIF of 1.00. Model LR 3, with a total air content threshold of 3.5%, has a similar but slightly less area under the ROC curve of 0.76 indicating an acceptable level of differentiation (Hosmer et al. 2013).

The results for a target durability factor of 80 or greater shown in Table 4-10 are very similar to those shown in Table 4-9. The areas under the ROC curves for models LR 5 through LR 8 are slightly higher than those of models LR 1 through LR 4, thus indicating that the models are better able to differentiate between concrete mixtures that do and do not have durability factors that are greater than or equal to the threshold. The AIC values of models LR 5 through LR 8 are also lower than those of models LR 1 through LR 4 which indicates a better fit. Between models LR 5 through LR 8, model LR 6 with a threshold total air content of 3.0% has the highest area under the ROC curve and the lowest AIC. This indicates that a total air content threshold of 3.0% is the best threshold at separating concrete mixtures that have a durability factor of 80 from those that do not.

4.9.2. Predictive Capacity of the SAM Number

Table 4-11 shows the logistic regression analysis results for models LR 9 through LR 11 which analyzed the SAM number's ability to provide an indication of whether a concrete mixture's durability factor is more or less than a threshold durability factor of 60. Table 4-12 shows the logistic regression analysis results for models LR 12 through LR 14 which perform the same function but for a durability factor threshold of 80.

Table 4-11. Results of Logistic Regression (LR) Analysis for Models 41 through LR 11.

Model	LR 9	LR 10	LR 11
>=x DF Threshold	**60**	**60**	**60**
>x SAM Number	**0.20**	**0.22**	**0.32**
Area Under ROC Curve	0.74	0.81	0.82
AIC	84.70	65.98	64.87
Maximum VIF	1.00	1.00	1.00
Variable	***p*-value**		
>x SAM number	3.40E-04	6.27E-04	4.42E-06
Variable	**β Coefficient**		
>x SAM number	-0.61	-1.01	-0.80

Table 4-12. Results of Logistic Regression (LR) Analysis for Models LR 12 through LR 14.

Model	LR 12	LR 13	LR 14
>=x DF Threshold	**80**	**80**	**80**
>x SAM Number	**0.20**	**0.22**	**0.32**
Area Under ROC Curve	0.74	0.76	0.79
AIC	84.70	82.05	74.73
Maximum VIF	1.00	1.00	1.00
Variable	***p*-value**		
>x SAM number	3.40E-04	1.25E-04	3.27E-06
Variable	**β Coefficient**		
>x SAM number	-0.61	-0.66	-0.73

In general, the results shown in Table 4-11 indicate then when the SAM number is used as a predictor of whether a concrete mixture will have a durability factor greater than 60, slightly higher areas under the ROC curve are achieved when compared to when the total air content is used. However, when comparing the areas under the ROC curve using the optimized total air content threshold of 3.5% (0.76) and the conservative recommended SAM number of 0.20 (0.74), the difference between the areas under the ROC curve is only 0.02 that favors the total air content threshold. If less conservative SAM numbers are used to predict durability, the area under the ROC curve increases significantly to either 0.81 or 0.82, depending on the SAM number. This suggests that the current SAM number recommendation of 0.20 is conservative, and that specifying a higher acceptable SAM number threshold may be appropriate. For instance, Figure 4-11 shows that if the SAM number threshold were moved to 0.25, less freeze-thaw resistant concrete would be rejected, and no additional non-freeze-thaw resistant concrete would be accepted. One might think that moving the SAM number threshold to 0.32 would advisable since model LR 11 has the highest area under the ROC curve and the lowest AIC of models LR 9 through LR 11, but this may be considered too unconservative given the limited dataset of 77 results upon which this analysis was based. Regardless of whether the SAM number threshold used is 0.20, 0.22, or 0.32, the corresponding coefficients of -0.61, -1.01, and -0.80 indicate that there is a significant expected drop in the probability of the durability being greater than or equal to 60 if the SAM number of a concrete mixture is greater than the threshold.

For models LR 12 through LR 14, the area under the ROC curve values are slightly less than those of models LR 9 through LR 11, thus indicating that the SAM number is better at predicting if concrete mixtures will have a higher probability of having durability factors of at least 60 than it is for durability factors of at least 80. This is to be expected as 80 is the more stringent durability factor requirement, and therefore there are less results that satisfy it. The AIC values for models LR 12 through LR 14 are also generally higher than those of models LR 9 through LR 11 which indicates that models LR 9 through LR 11 are the better fitting models. Additionally, the negative coefficients for models LR 12 through LR 14 indicate that there is a significant decrease in the probability of a concrete mixture having a durability factor of at least 80 if the concrete mixture's SAM number exceeds the threshold for the given model.

4.10 Summary

In this chapter, data collected from literature was analyzed and discussed. The data was analyzed by three methods: 1) splitting it into quartiles based on thresholds and grouping results into categories, 2) multivariable linear regression analysis, and 3) logistic regression analysis. An optimized total air content threshold, defined as the total air content threshold that best accomplishes the dual goals of minimizing the amount of potentially non-durable concrete that is placed and accepted in the field and minimizing the amount of potentially durable concrete that is rejected in the field, was determined for target durability factors of 60 and 80. Also, relationships between the total air content, spacing factor, SAM number, and durability factor were established and evaluated.

The key findings of the analysis performed in this chapter are as follows:

- For concrete mixtures without PC HRWR admixture, the optimal total air content threshold for a target durability factor of 60 is 3.5%. This results in a false positive rate of 2% and a false negative rate of 21%. When using a total air content threshold of 2.5%, the false positive rate is 17%, while the false negative rate is 9%.
- For concrete mixtures without PC HRWR admixture, the optimal total air content threshold for a target durability factor of 80 is 3.5%. This results in a false positive rate of 4% and a false negative rate of 13%.
- A SAM number threshold of 0.20 is able to identify concrete mixtures with a spacing factor of 0.008 inches or less 89%, of the time with a false positive rate of 11%. This is better than a total air content threshold of 3.5% which is able to identify concrete

mixtures with a spacing factor of 0.008 inches or less 77% of the time with a false positive rate of 20%.

- The following thresholds are able to identify concrete mixtures with durability factors of 60 or greater in accordance with AASHTO T 161 (2022) at the following rates:
    - A total air content threshold of 3.5%: 77% correct identification with a false positive rate of 2%.
    - A spacing factor threshold of 0.008 inches: 62% correct identification with a false positive rate of 2%.
    - A SAM number threshold of 0.20: 71% correct identification with a false positive rate of 1%.

- Of the thresholds evaluated, the total air content threshold of 3.5% is able to correctly predict a concrete mixture's durability factor with the highest accuracy.
- Multivariable linear regression analysis yielded conflicting results regarding the influence of w/cm on concrete's freeze-thaw resistance. Results in Section 4.8.1 suggested that decreasing the w/cm slightly improved the freeze-thaw resistance of concrete mixtures while results in Section 4.8.2 found the opposite. Given the conflicting findings, no conclusion can be drawn regarding the influence of the w/cm on the freeze-thaw resistance of air-entrained concrete mixtures. Even if the direction of the signs of the w/cm coefficients were the same, the insignificant magnitude of the coefficients of the w/cm variable compared to that of the total air

content and spacing factor variables suggests that w/cm is much less influential than the air-void system in impacting concrete's freeze-thaw resistance. The magnitude of the w/cm coefficients are 1/4 to 2/5 those of the total air content and 1/4 to 1/3 those of the spacing factor, depending on the model.

- Multivariable linear regression analysis models MVLR 8, MVLR 9, and MVLR 16 through MVLR 19 and logistic regression analysis models LR 15 through LR 18 suggest that the inclusion of synthetic air-entraining admixture as opposed to the inclusion of natural (wood rosin) air-entraining admixture is not statistically significant to the α=0.05 level, while models MVLR 10 through MVLR 14 suggest the opposite. Given these contradictory results, the effects of the use of synthetic air-entraining admixture as opposed to natural (wood rosin) air-entraining admixtures on a concrete mixture's air-void system and durability factor is inconclusive.
- PC HRWR admixtures may adversely impact the air-void system, meaning that in order to achieve adequate freeze-thaw resistance, a higher total air content may be required. The impact of PC HRWR admixtures on the air-void system varies depending on the dosage and chemical composition of the PC HRWR admixture used.

CHAPTER 5

RESULTS AND DISCUSSION OF LABORATORY TESTING DATA

5.1 Introduction

In this chapter, data collected from laboratory testing are analyzed and discussed. Optimal total air content thresholds are established for durability factor targets of 60 and 80 and are compared. Relationships between indicators of freeze-thaw durability and the durability factor are established and compared. The utility, reliability, variability, and operational complexity of the SAM meter are also evaluated. The influence of the w/cm, strength, and type of air-entraining admixture on the concrete mixtures' freeze-thaw resistance is determined.

5.2 Experimental Test Results

This section contains fresh and hardened concrete properties of concrete mixtures tested in this study.

5.2.1. Fresh Concrete Properties

Table 5-1 shows abbreviations used in Table 5-2 and Table 5-3, which show fresh concrete properties obtained from laboratory testing.

Table 5-1. Abbreviations used in Table 5-2 and Table 5-3.

Abbreviation	Definition
TAC 1	1st Total Air Content Result from Type B Pressure Meter
TAC 2	2nd Total Air Content Result from Type B Pressure Meter
SAM TAC 1	1st Total Air Content Result from SAM Meter
SAM TAC 2	2nd Total Air Content Result from SAM Meter
SAM #1	1st SAM Number Result
SAM #2	2nd SAM Number Result

Table 5-2. Fresh Concrete Properties Obtained from Laboratory Testing of Mixtures with w/cm=0.35 and 0.40.

	Test Results					
Mixture ID	**TAC 1**	**TAC 2**	**SAM TAC 1**	**SAM TAC 2**	**SAM #1**	**SAM #2**
	(%)	**(%)**	**(%)**	**(%)**	**(-)**	**(-)**
0.35: N+PC1 1	7.0	6.0	6	5.5	ERR	0.25
0.35: N+PC1 2	6.2	4.8	6.3	4.3	0.30	0.46
0.35: S+PC2 1	4.1	2.5	3.8	2.0	0.43	0.06
0.35: S+PC2 2	2.7	3.3	N/D	N/D	N/D	N/D
0.35: S+PC2 3	5.3	N/D	N/D	N/D	N/D	N/D
0.35: S+PC2 4	3.1	2.5	3.2	2.8	0.50	0.55
0.35: S+PC2 5	3.5	2.5	3.9	2.5	0.43	0.55
0.35: PC1 1	4.8	3.5	3.8	N/D	0.47	N/D
0.40: S+WR 1	2.8	2.5	2.8	2.6	0.68	0.70
0.40: S+WR 2	3.0	2.4	2.8	2.8	ERR	0.71
0.40: S+WR 3	3.8	N/D	3.6	N/D	0.39	N/D

Note: N/D: Not Determined, ERR: Equipment Error

Table 5-3. Fresh Concrete Properties Obtained from Laboratory Testing of Mixtures with w/cm=0.45 and 0.50.

	Test Results					
Mixture ID	**TAC 1**	**TAC 2**	**SAM TAC 1**	**SAM TAC 2**	**SAM #1**	**SAM #2**
	(%)	**(%)**	**(%)**	**(%)**	**(-)**	**(-)**
0.45: N+WR 1	3.5	N/D	3.3	2.7	0.60	0.34
0.45: N+WR 2	2.8	N/D	3.7	2.4	ERR	0.07
0.45: N+WR 3	4.3	4.5	4.3	4.3	ERR	0.51
0.45: N+WR 4	5.6	4.5	2.1	3.5	ERR	ERR
0.45: N+WR 5	2.6	2.1	2.1	1.7	ERR	ERR
0.45: N+WR 6	4.2	3.4	4.6	2.6	0.55	ERR
0.45: N+WR 7	3.5	3.0	3.5	3.0	0.23	0.49
0.45: N+WR 8	2.3	2.0	2.6	1.7	0.56	0.04
0.45: N+WR 9	2.6	2.1	2.8	2.4	0.60	0.57
0.45: N+WR 10	3.1	1.9	4.2	3.6	0.42	0.64
0.45: S+WR 1	2.3	2.2	2.6	2.4	0.55	0.67
0.45: S+WR 2	4.3	3.5	5.6	3.2	0.38	0.08
0.45: S+WR 3	4.7	1.8	4.2	4.3	ERR	ERR
0.45: S+WR 4	4.6	3.0	4.8	3.6	0.31	0.19
0.45: S+WR 5	2.9	2.7	3.1	2.5	0.24	0.25
0.45: S+WR 6	4.0	2.7	4.5	3.4	0.64	0.24
0.45: S+WR 7	3.4	2.8	3.6	3.3	0.33	0.71
0.45: WR 1	2.3	1.8	2.2	2.4	0.04	0.34
0.50: S+WR 1	4.1	2.8	4.3	3.0	0.16	0.29
0.50: S+WR 2	4.5	3.0	5.1	2.9	0.33	0.22
0.50: S+WR 3	2.2	2.2	3.0	2.1	N/D	0.10
0.50: S+WR 3	1.8	1.8	2.2	1.6	0.67	0.71
0.50: S+WR 5	3.0	N/D	3.8	N/D	0.41	N/D
0.50: S+WR 6	3.3	3.1	3.1	2.9	0.37	0.47

Note: N/D: Not Determined, ERR: Equipment Error

5.2.2. Hardened Concrete Properties

Table 5-4 shows abbreviations used in Table 5-5 and Table 5-6, which show hardened concrete properties obtained from laboratory testing.

Table 5-4. Abbreviations used in Table 5-5 and Table 5-6.

Result	Definition
DF	Durability Factor
f'_c 28	Compressive Strength at 28 days
f'_c 56	Compressive Strength at 56 days
H TAC	Hardened Total Air Content
SS	Specific Surface
SF	Spacing Factor

Table 5-5. Hardened Concrete Properties Obtained from Laboratory Testing of Mixtures with w/cm=0.35 and 0.40.

	Test Result					
Mixture ID	**DF**	f'_c **28**	f'_c **56**	**H TAC**	**SS**	**SF**
	--	**(psi)**	**(psi)**	**(%)**	**(in.^{2}/in.^{3})**	**(in.)**
0.35: N+PC1 1	75	9760	N/D	--	--	--
0.35: N+PC1 2	43	7780	8210	--	--	--
0.35: S+PC2 1	15	11960	12760	--	--	--
0.35: S+PC2 2	12	10670	11200	--	--	--
0.35: S+PC2 3	71	9500	10060	--	--	--
0.35: S+PC2 4	17	11050	11560	--	--	--
0.35: S+PC2 5	21	10780	10670	--	--	--
0.35: PC1 1	51	9990	10530	--	--	--
0.40: S+WR 1	60	7810	8550	--	--	--
0.40: S+WR 2	39	7840	8590	--	--	--
0.40: S+WR 3	67	7380	8180	--	--	--

Note: N/D: Not Determined

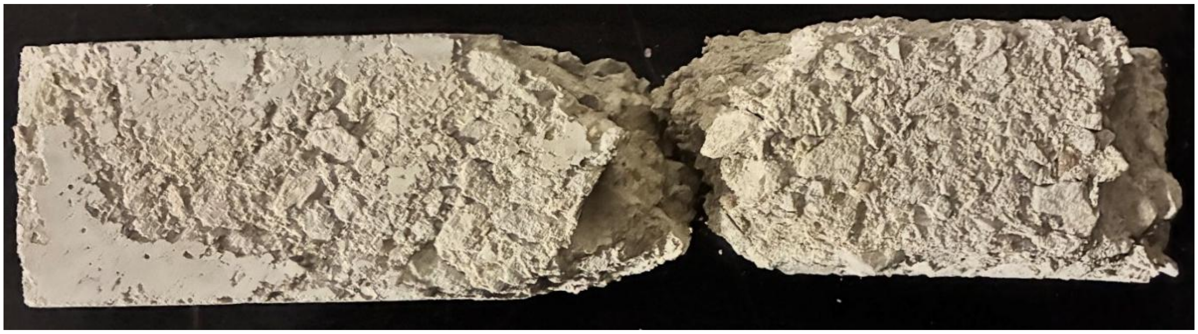
Table 5-6. Hardened Concrete Properties Obtained from Laboratory Testing of Mixtures with w/cm=0.45 and 0.50.

	Test Result					
Mixture ID	**DF**	f'_c **28**	f'_c **56**	**H TAC**	**SS**	**SF**
	--	**(psi)**	**(psi)**	**(%)**	**(in.^{2}/in.^{3})**	**(in.)**
0.45: N+WR 1	6	N/A	6550	3.6	228	0.026
0.45: N+WR 2	21	6230	7000	3.1	341	0.018
0.45: N+WR 3	74	5260	5680	--	--	--
0.45: N+WR 4	84	6370	7380	--	--	--
0.45: N+WR 5	13	6600	7290	2.6	310	0.022
0.45: N+WR 6	76	6930	7610	--	--	--
0.45: N+WR 7	81	6890	7970	3.5	342	0.017
0.45: N+WR 8	3	6700	7200	--	--	--
0.45: N+WR 9	33	6740	7330	2.8	418	0.015
0.45: N+WR 10	56	8470	9440	--	--	--
0.45: S+WR 1	13	6570	7100	--	--	--
0.45: S+WR 2	84	6300	6960	--	--	--
0.45: S+WR 3	69	5920	6520	4.8	578	0.008
0.45: S+WR 4	80	5800	6430	--	--	--
0.45: S+WR 5	70	N/D	N/D	3.5	558	0.01
0.45: S+WR 6	80	5920	6630	--	--	--
0.45: S+WR 7	84	6540	7420	--	--	--
0.45: WR 1	4	6470	N/A	--	--	--
0.50: S+WR 1	74	5670	6360	--	--	--
0.50: S+WR 2	82	5100	5760	--	--	--
0.50: S+WR 3	74	5500	6230	2.3	522	0.013
0.50: S+WR 5	75	5264	5980	--	--	--
0.50: S+WR 6	64	5810	6510	--	--	--

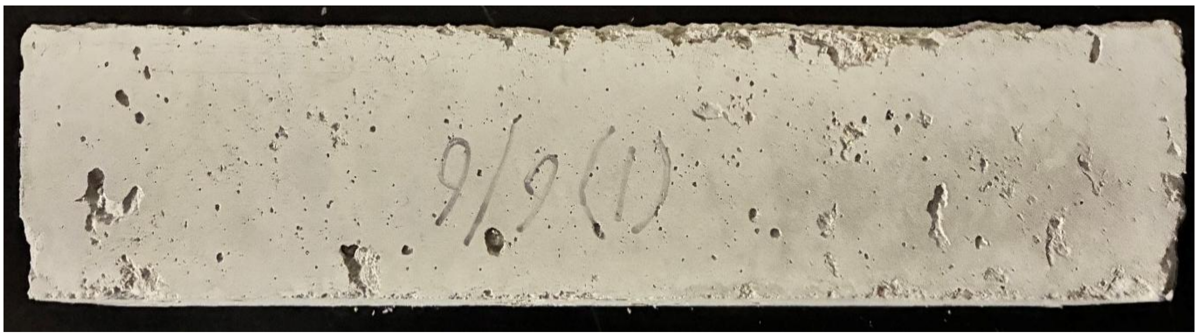
Note: N/D: Not Determined

5.3 Visual Analysis of Concrete Prisms Subjected to AASHTO T 161 (2022) Testing

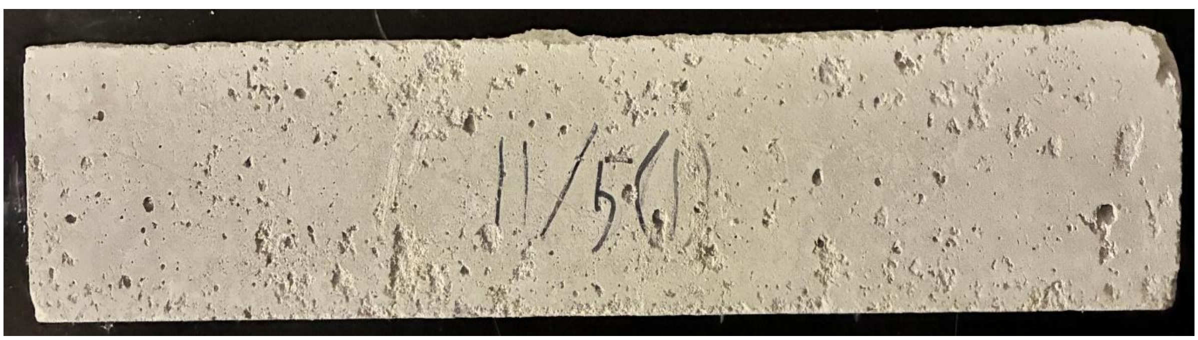
Figure 5-1 and Figure 5-2 show the top and side surfaces of prisms subjected to AASHTO T 161 (2022) testing. The damage was assessed by resonant frequency testing to determine the durability factor.



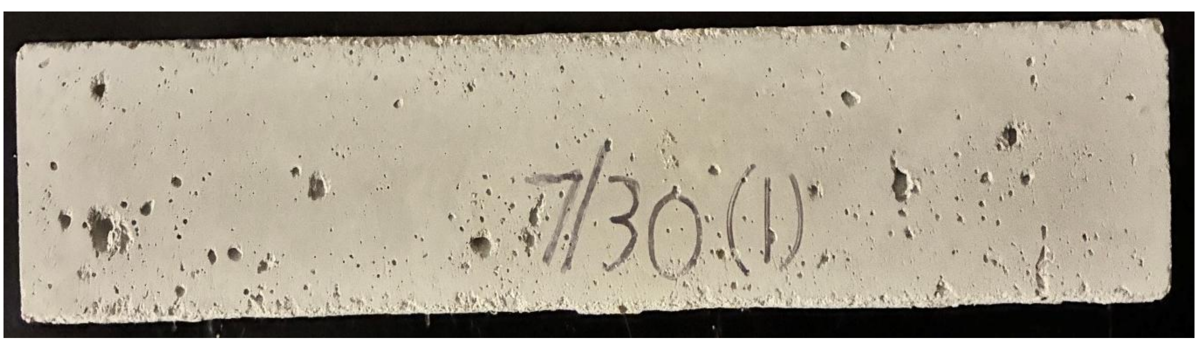
(a) Durability Factor = 4, Mixture ID = 0.45: WR 1



(b) Durability Factor: 33, Mixture ID = 0.45: N+WR 9



(c) Durability Factor: 74, Mixture ID = 0.50: S+WR 3



(d) Durability Factor: 84, Mixture ID = 0.45: S+WR 2

Figure 5-1. Top Surfaces of Prisms with Varying Durability Factors.

(a) Durability Factor: 4, Mixture ID = 0.45: WR 1

(b) Durability Factor: 33, Mixture ID = 0.45: N+WR 9

(c) Durability Factor: 74, Mixture ID = 0.50: S+WR 3

(d) Durability Factor: 84, Mixture ID = 0.45: S+WR 2

Figure 5-2. Side Surfaces of Prisms with Varying Durability Factors.

5.4 Minimum Total Air Content Optimization for a Target Durability Factor of 60 of Greater

Given the unpredictable freeze-thaw resistance of air-entrained concrete mixtures made with PC HRWR admixtures, in this section concrete mixtures made with PC HRWR admixtures were analyzed separately from those without PC HRWR admixtures. Mixtures with PC HRWR admixture will also tend to have low w/cm (i.e., high strength) and thus used mostly in prestressed, precast concrete applications.

A target durability factor of 60 was selected because it provides an indication of an acceptable level of freeze-thaw resistance (Newlon 1978b). Although a durability factor of 80 provides an indication of excellent freeze-thaw resistance (Obla et al. 2016), a target durability factor of 80 was not selected for ALDOT structures since they are exposed to fewer cycles of freezing and thawing than structures located in Northern parts of the United States and since they are not exposed to deicing chemicals.

5.4.1. Concrete mixtures without Polycarboxylate-Based, High-Range Water-Reducing Admixtures

Figure 5-3 shows the durability factor versus total air content results obtained from laboratory testing for mixtures containing Type A/D water-reducing admixture. Also shown is a vertical line showing the optimized total air content threshold of 3.5% from Section 4.3 and a horizontal line showing an acceptable durability factor of 60.

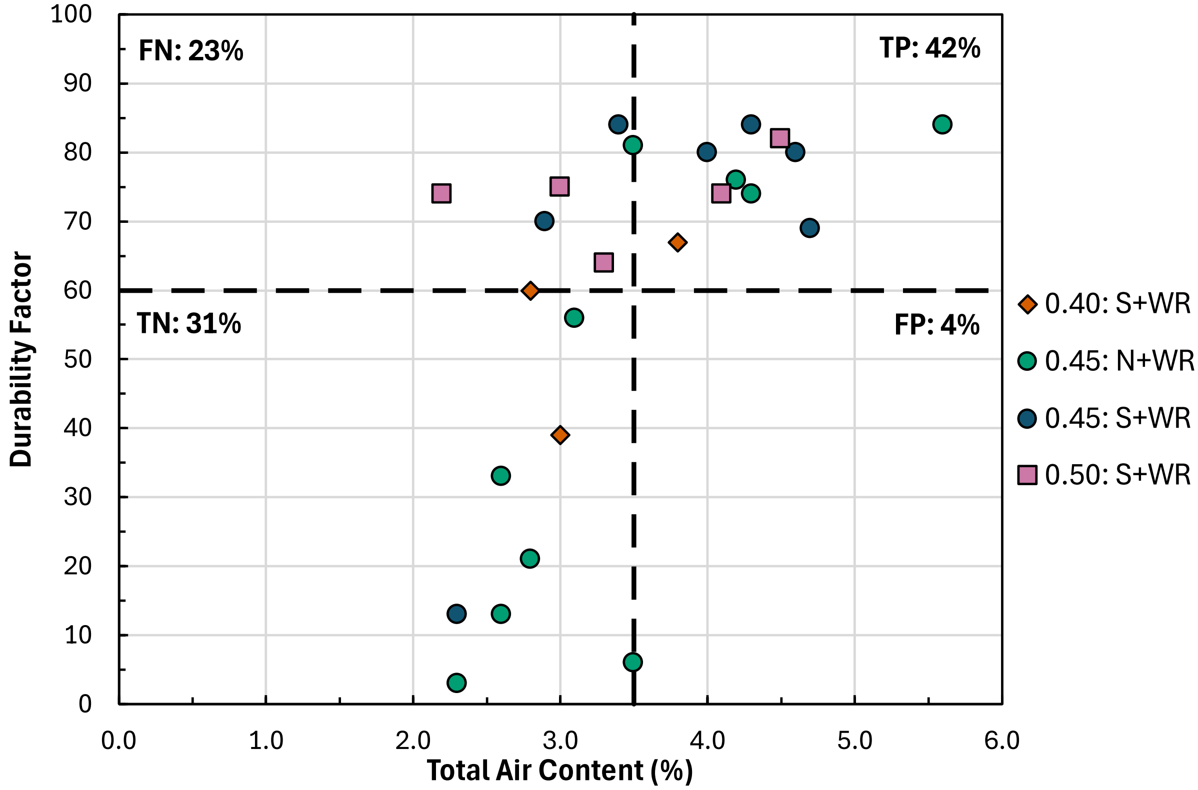


Figure 5-3. Durability Factor versus Total Air Content (%) data obtained from laboratory testing (n = 26). The vertical line shows the optimized total air content of 3.5% from Chapter 4, and the horizontal line shows an acceptable durability factor of 60.

The results show that concrete mixtures made with w/cm=0.40, 0.45, and 0.50 perform similarly when their total air contents are similar. This suggests that the quality of the air-void system, as measured by the total air content, is a far better indicator of freeze-thaw resistance than the w/cm. This is supported by Tanesi and Meininger (2006) who found that the w/cm did not appear to significantly influence the freeze-thaw resistance of concrete mixtures with w/cm=0.40 to 0.50 made with vinsol resin air-entraining admixture. They also found that the correlation coefficient between the w/cm and the durability factor of their concrete mixtures was only 0.04, a miniscule value compared to the far greater correlation coefficient of 0.78 between the total air content and the durability factor (Tanesi and Meininger 2006).

The data shows that if the optimized total air content threshold of 3.5% is used as a criterion for predicting concrete mixtures' freeze-thaw resistance, the false positive rate is only 4%. Other threshold total air contents including 2.5, 3.0, and 4.0% were also used in the optimization process. Figure 5-4 and Figure 5-5 show the false positive and false negative rates, respectively, for various total air content threshold values.

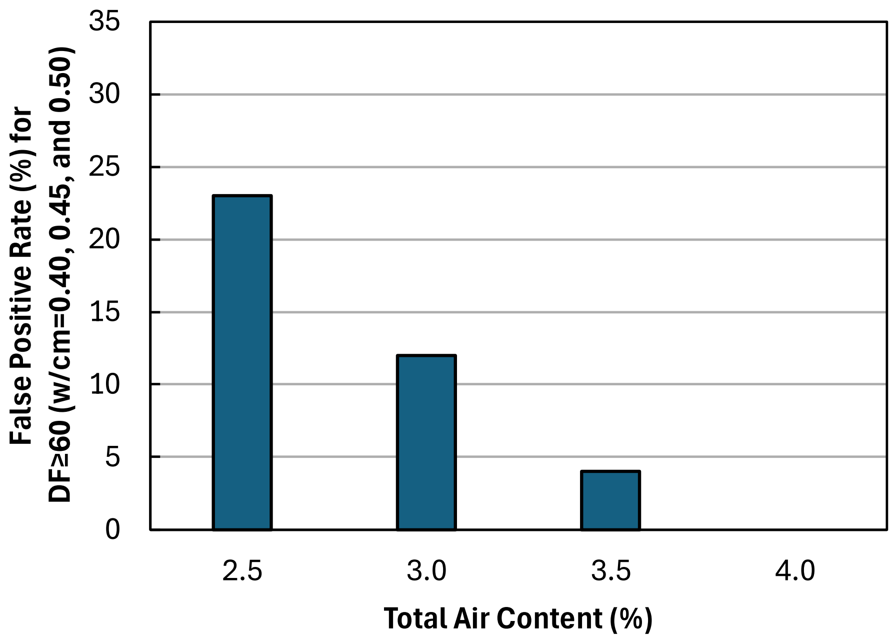


Figure 5-4. False positive rates for a durability factor threshold of 60 and total air contents of 2.5, 3.0, 3.5, and 4.0%.

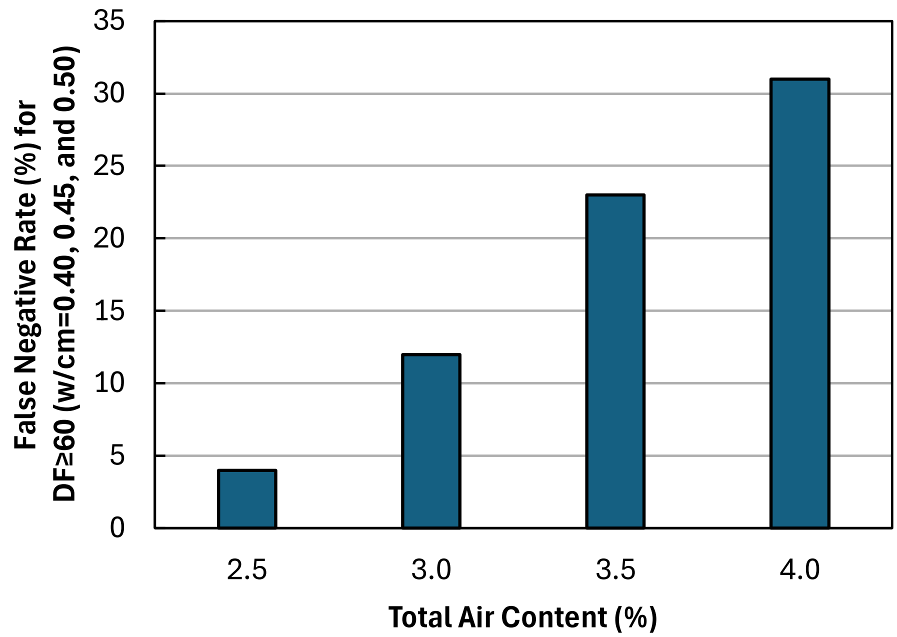


Figure 5-5. False negative rates for a durability factor threshold of 60 and total air contents of 2.5, 3.0, 3.5, and 4.0%.

Figure 5-4 shows that a false positive rate of 4% can be achieved if a total air content threshold of 3.5% is used to divide the laboratory testing data from this study. This implies that if ALDOT requires all air-entrained concrete mixtures without PC HRWR admixtures to have a total air content of at least 3.5% as a condition of acceptance for projects, only a very small portion of accepted concrete mixtures will have unacceptable freeze-thaw resistance. If a total air content threshold of 4.0% is used as a criterion of acceptance, the false positive rate falls to 0%. This suggests that for an air-entrained concrete mixture that does not contain PC HRWR admixture and has a total air content of at least 4.0%, the probability of it not having an acceptable durability factor is virtually zero. However, Figure 5-5 shows that increasing the total air content threshold from 3.5 to 4.0% increases the false negative rate from 23 to 31%, a considerable downside for contractors. This means that the majority of concrete mixtures with total air contents in the 3.5 to 4.0% range will have acceptable freeze-thaw resistance but will still be rejected in the field. Therefore, given the false positive and false negative rates shown in Figure 5-4 and Figure 5-5, the optimal total air content for concrete mixtures without PC HRWR admixture is 3.5%. This matches the optimal total air content threshold derived from data obtained from literature in Section 4.3.

5.4.2. Concrete mixtures made with Polycarboxylate-Based, High-Range Water-Reducing Admixtures

Figure 5-6 shows the durability factor versus total air content results obtained from laboratory testing for mixtures containing PC HRWR admixtures. The data reveals that none of the evaluated total air content thresholds are adequate to ensure freeze-thaw resistant concrete when saturated. These include the current ALDOT Section 501 minimum total air content of 2.5% for Class B concrete, the optimized 3.5% total air content threshold discussed in Section 4.3, and the ALDOT Section 513 target total air content of 4.5% for prestressed concrete bridge members. Figure 5-6 shows that if the optimized total air content threshold of 3.5% is used, there is a false positive rate of 50%. Consequently, a substantial portion of concrete mixtures made with PC HRWR admixtures that are accepted under this criterion would potentially not exhibit acceptable freeze-thaw resistance.

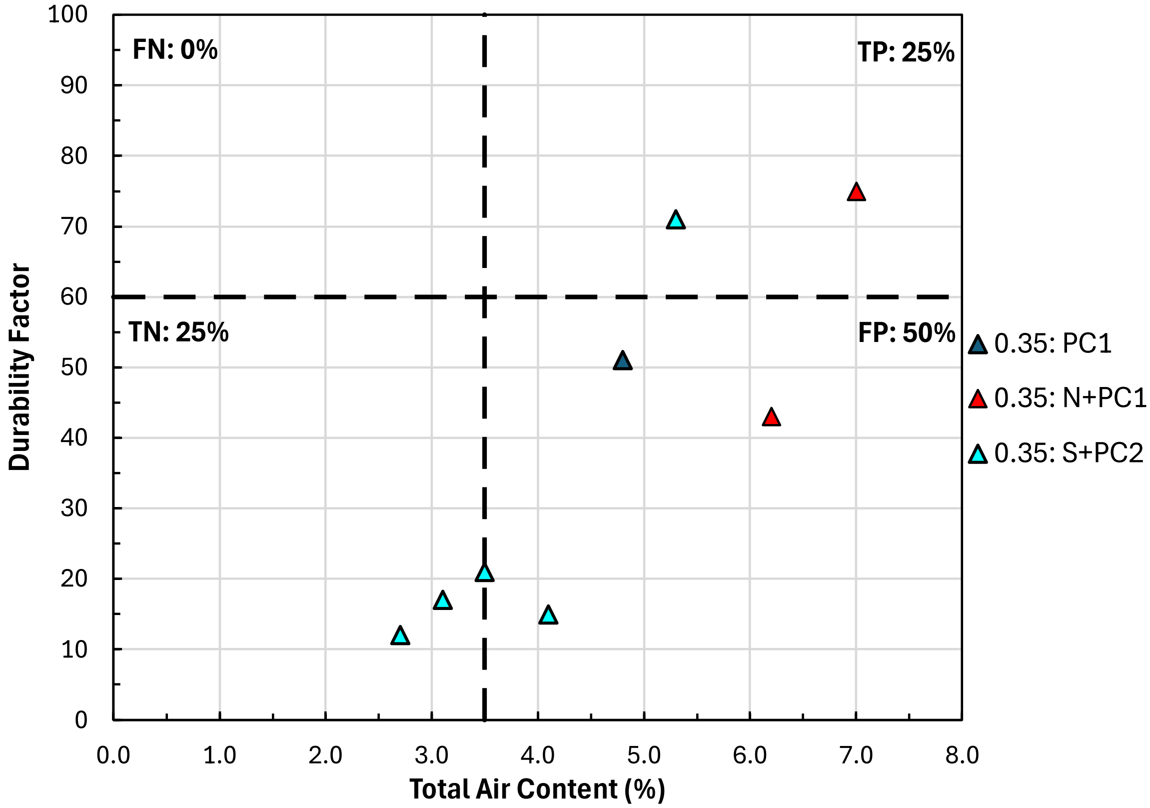


Figure 5-6. Durability Factor versus Total Air Content (%) data obtained from laboratory testing (n = 8). The vertical line shows the optimized total air content of 3.5% from Chapter 4, and the horizontal line shows an acceptable durability factor of 60.

Figure 5-6 also implies that for concrete mixtures made with synthetic air-entraining admixtures and PC2, a total air content of at least 5.0% is required for them to achieve an acceptable durability factor of at least 60. For mixtures made with natural air-entraining admixtures and PC1, this value appears to be 7.0%. These findings align with the finding of Freeman (2012) who found that in order to achieve a given spacing factor, a higher volume of air is needed in concrete mixtures containing PC HRWR admixture. These findings suggest that concrete mixtures made with PC HRWR admixtures have an inadequate air-void system. Because the air voids in some concrete mixtures containing PC HRWR admixture are larger and spaced far apart, the air-void system is unable to relieve the hydraulic and osmotic pressures that build up as a result of internal freezing of pore water.

However, care should be taken to not assume that the adverse effects of using PC HRWR admixture apply for every PC HRWR admixture. Freeman (2012) found that two concrete mixtures containing 5.5 and 5.7% total air content and two different PC HRWR admixtures passed AASHTO T 161 (2022) testing, while three other concrete mixtures containing 4.5, 5.0, and 5.2% total air content and three different PC HRWR admixtures failed AASHTO T 161 (2022) testing. This suggests that the freeze-thaw resistance of concrete mixtures made with different PC HRWR admixtures is variable and is dependent on the specific chemical composition of the PC HRWR admixture used. Given these findings, concrete structures made using PC HRWR admixture should be isolated from simultaneous exposure to moisture and cycles of freezing and thawing. Alternatively, additional freeze-thaw testing should be performed to test the impact of different PC HRWR admixtures on concrete mixtures' freeze-thaw resistance. This would allow ALDOT to determine which PC HRWR admixtures deleteriously affect concrete mixtures' air-void systems and how much entrained air is needed to ensure an adequate level of freeze-thaw resistance.

5.5 Minimum Total Air Content Optimization for a Target Durability Factor of 80 of Greater

The process of sorting AASHTO T 161 (2022) testing results into categories based on their durability factors and total air contents was repeated for a target durability factor of 80 or greater. This was only done for concrete mixtures that do not contain PC HRWR admixtures since none of the concrete mixtures containing PC HRWR admixture tested in this study had a durability factor of 80 or greater. False positive and false negative rates are shown in Figure 5-7 and Figure 5-8, respectively.

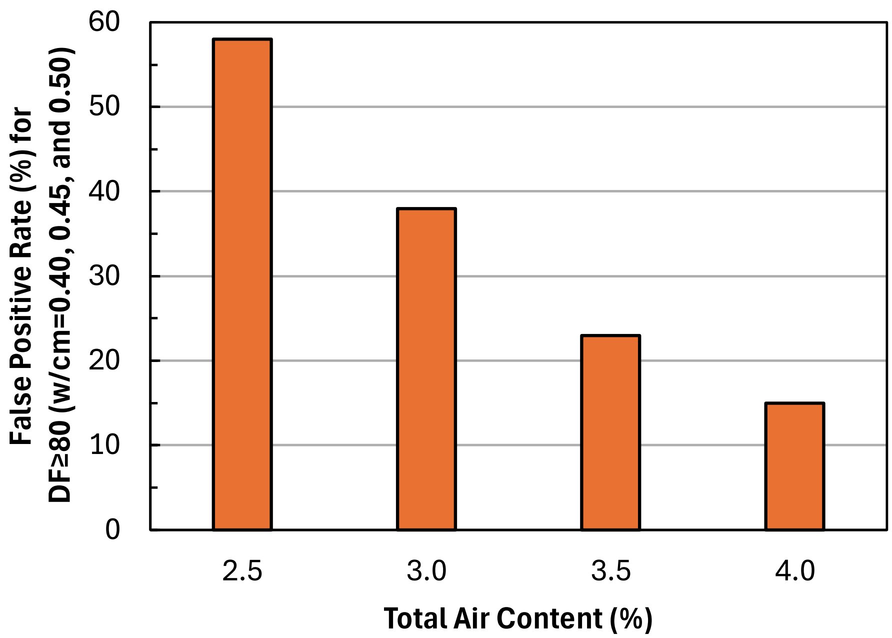


Figure 5-7. False positive rates for a durability factor threshold of 80 and total air contents of 2.5, 3.0, 3.5, and 4.0%.

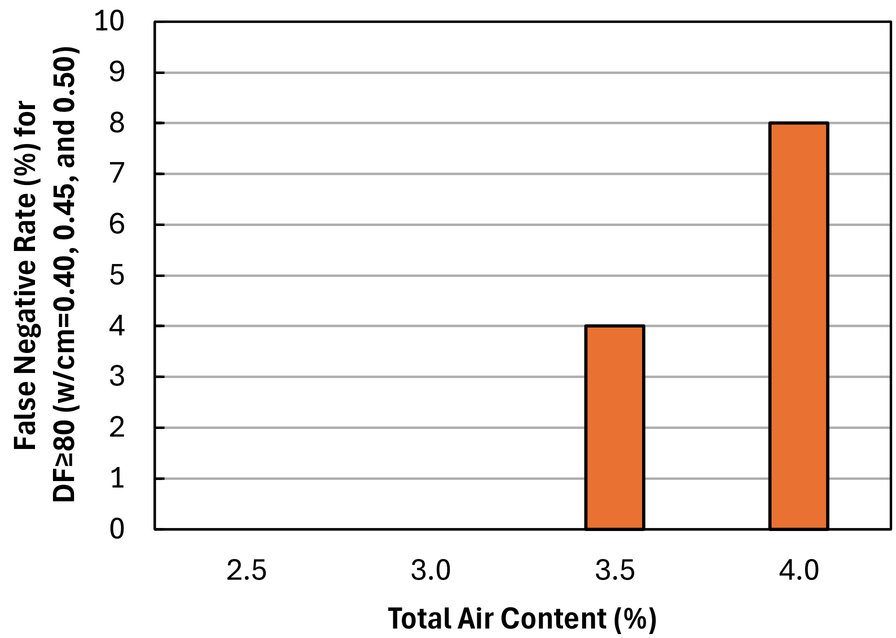


Figure 5-8. False negative rates for a durability factor threshold of 80 and total air contents of 2.5, 3.0, 3.5, and 4.0%.

Figure 5-7 indicates that the false positive rate associated with a total air content threshold of 2.5%, the current ALDOT Section 501 minimum total air content requirement, is 58%. This indicates that a significant portion of concrete mixtures accepted in the field may not have a durability factor of 80 or greater. In other words, a significant portion of accepted concrete mixtures may not have excellent freeze-thaw resistance under the current ALDOT Section 501 minimum total air content requirement. The percentage of false positive results can be reduced from 58 to 15% by increasing the total air content threshold from 2.5 to 4.0%. As shown in Figure 5-8, this would increase the false negative rate from 0 to 8%. These findings suggest that if a more conservative durability factor of 80 is targeted, the optimal total air content threshold is 4.0%. This 4.0% optimal total air content threshold is 0.5% greater than the optimal total air content threshold of 3.5% found by analyzing data obtained from literature in Section 4.5 and when using a durability factor of 60. One potential reason for this is that the size of the dataset analyzed in this section is only 26, whereas in Section 4.5, 391 results were analyzed. Given this 0.5% total air content difference, using the 3.5% threshold from the larger dataset seems appropriate.

5.6 Comparison of False Positive and False Negative Rates for Target Durability Factors of 60 and 80

Figure 5-9 shows a comparison of false positive results for target durability factors of 60 and 80 for total air content thresholds of 2.5, 3.0, 3.5, and 4.0%. Results from concrete mixtures containing PC HRWR admixture are not included in the comparison since no concrete mixtures that contained PC HRWR admixture achieved a durability factor of 80 or greater.

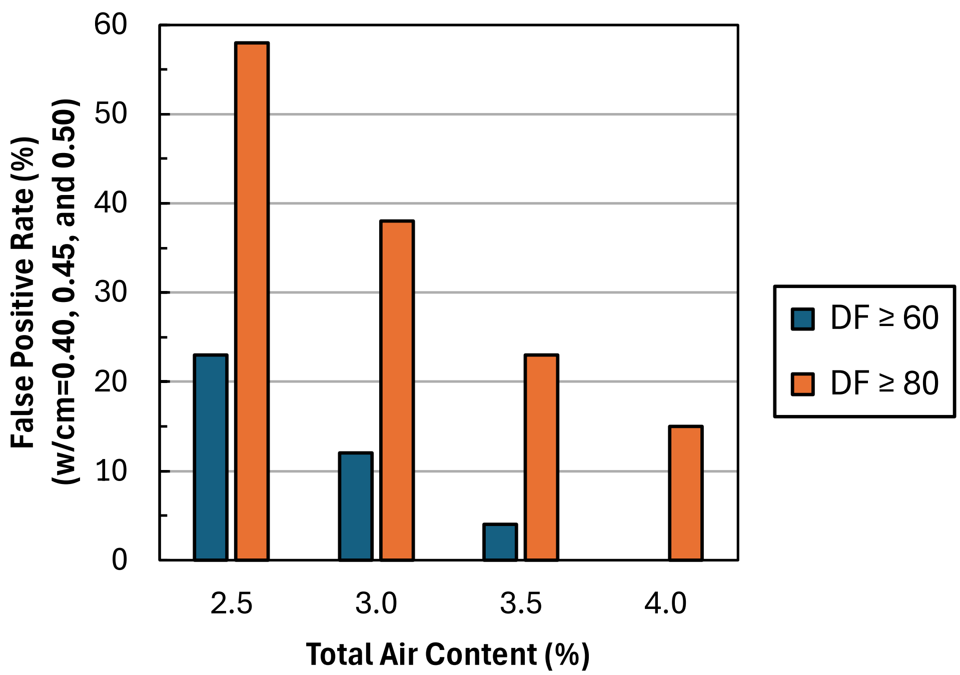


Figure 5-9. False positive rates for durability factor thresholds of 60 and 80 and total air contents of 2.5, 3.0, 3.5, and 4.0%.

Figure 5-10 shows a comparison of false negative results for target durability factors of 60 and 80 for total air content thresholds of 2.5, 3.0, 3.5, and 4.0%.

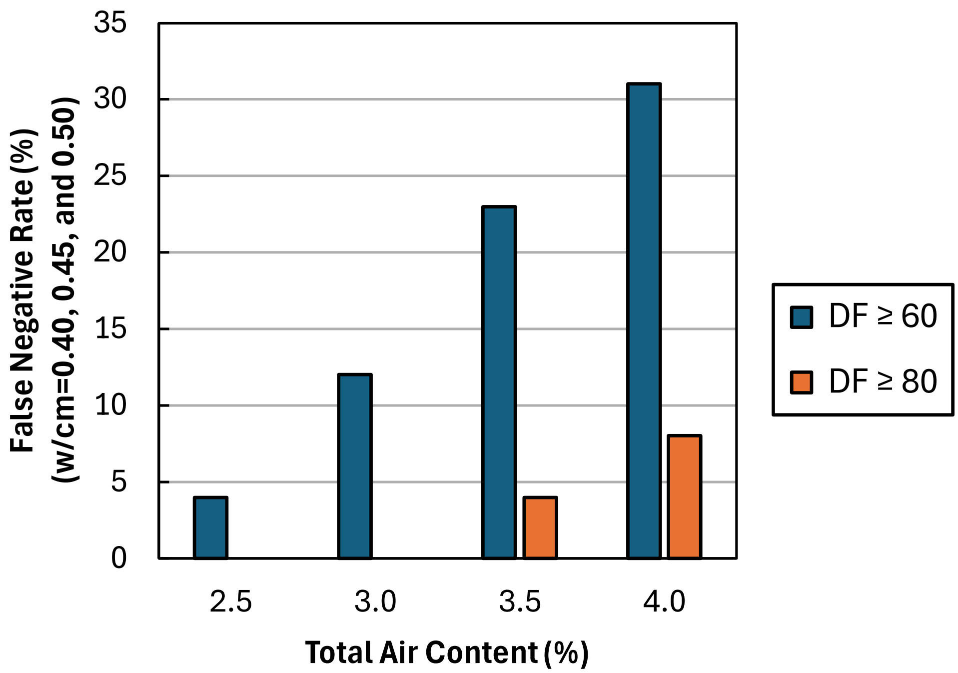


Figure 5-10. False negative rates for durability factor thresholds of 60 and 80 and total air contents of 2.5, 3.0, 3.5, and 4.0%.

As expected, Figure 5-9 indicates that at each total air content threshold, the false positive rate is higher for the more conservative target durability factor of 80 than it is for the target durability factor of 60. This indicates that more concrete mixtures that are accepted in the field will be incorrectly predicted to achieve a durability factor of at least the target when a target durability factor of 80 is used instead of 60. Conversely, Figure 5-10 indicates that if a less stringent durability factor of 60 is considered by ALDOT to be acceptable, more potentially acceptable concrete mixtures will get rejected in the field than if a durability factor of 80 is considered to be acceptable. Given these findings and the findings in Section 4.6, if a durability factor of 60 is desired, the optimized total air content threshold is 3.5%. If a durability factor of 80 is desired, the optimized total air content threshold is either 3.5 or 4.0%, depending on whether more significance is placed on data obtained from literature or laboratory testing. The 391 test results obtained from literature suggest that the optimized total air content threshold is 3.5%, and this value is appropriate because it is based on a much larger dataset.

5.7 Relationships between Total Air Content, SAM Number, Spacing Factor, and Durability Factor

To better understand the relationships between the total air content, SAM number, spacing factor, and durability factor, the process of evaluating results into classes described in Section 4.3 was repeated for different parameters. Results from concrete mixtures both containing and without PC HRWR admixture are included in this section. First, the relationship between two predictors of durability, total air content and spacing factor, was investigated using the optimized minimum total air content of 3.5% and the ACI 201.2 (2023) recommended maximum spacing factor of 0.008 inches to ensure freeze-thaw durability (ACI 201.2 2023). The spacing factor versus total air content results and classifications are shown in Figure 5-11. Figure 5-11 shows that whether the spacing factor is greater than or less than 0.008 inches can be correctly predicted 75% (TP=13 and TN=62%) of the time with a false positive rate of 25% based on whether the total air content is greater or less than 3.5%. These rates are similar to the rates in Section 4.7 in which it was found that the spacing factor could be correctly predicted using the total air content 77% of the time with a false positive rate of 20%.

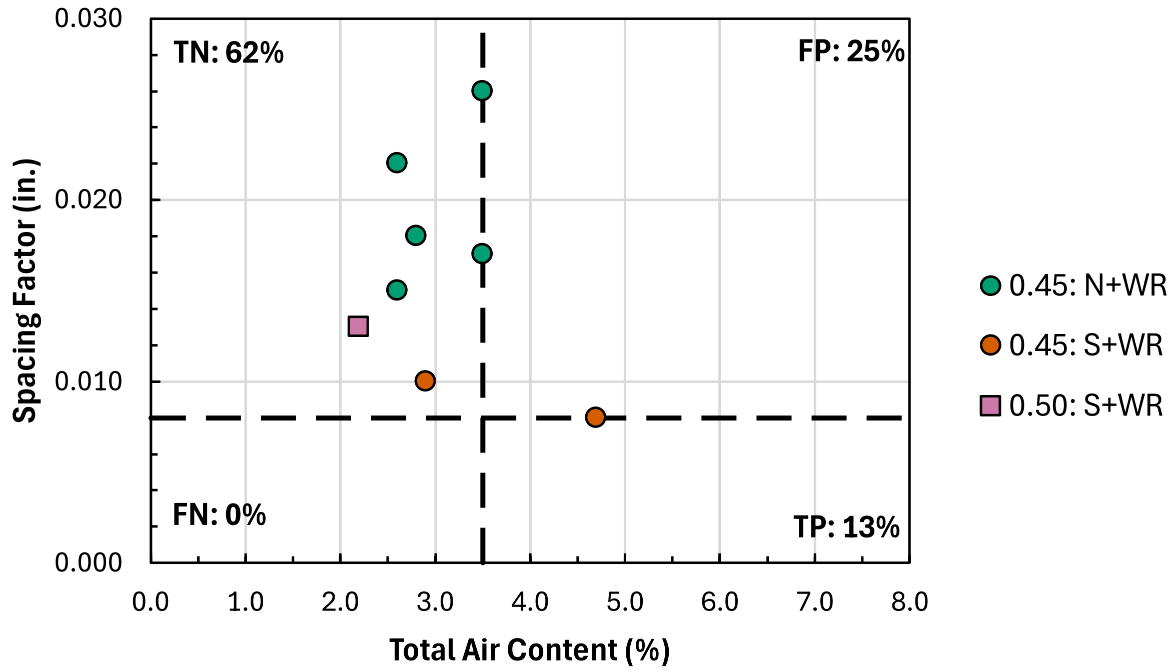


Figure 5-11. Spacing Factor (in.) versus Total Air Content (%) data obtained from laboratory testing (n = 8). The vertical line is the optimized total air content of 3.5%, and the horizontal line is the ACI 201.2 (2023) recommended maximum spacing factor of 0.008 in.

Next, the relationship between the SAM number and the spacing factor was investigated using the conservative maximum SAM number threshold of 0.20 recommended by Ley et al. (2017) and a spacing factor of 0.008 inches. The spacing factor versus SAM number results and classifications are shown in Figure 5-12. Figure 5-12 shows that whether the spacing factor is greater or lesser than 0.008 inches can be correctly predicted using the SAM number 100% of the time with a false positive rate of 0%, an improvement in accuracy compared to predictions made using the total air content. This supports the finding in Section 4.7, in which it was found that the SAM number correctly predicts the spacing factor 89% of the time with a false positive rate of 11%. These findings support the conclusion that the SAM number is a better indicator of a concrete mixture's spacing factor than the total air content.

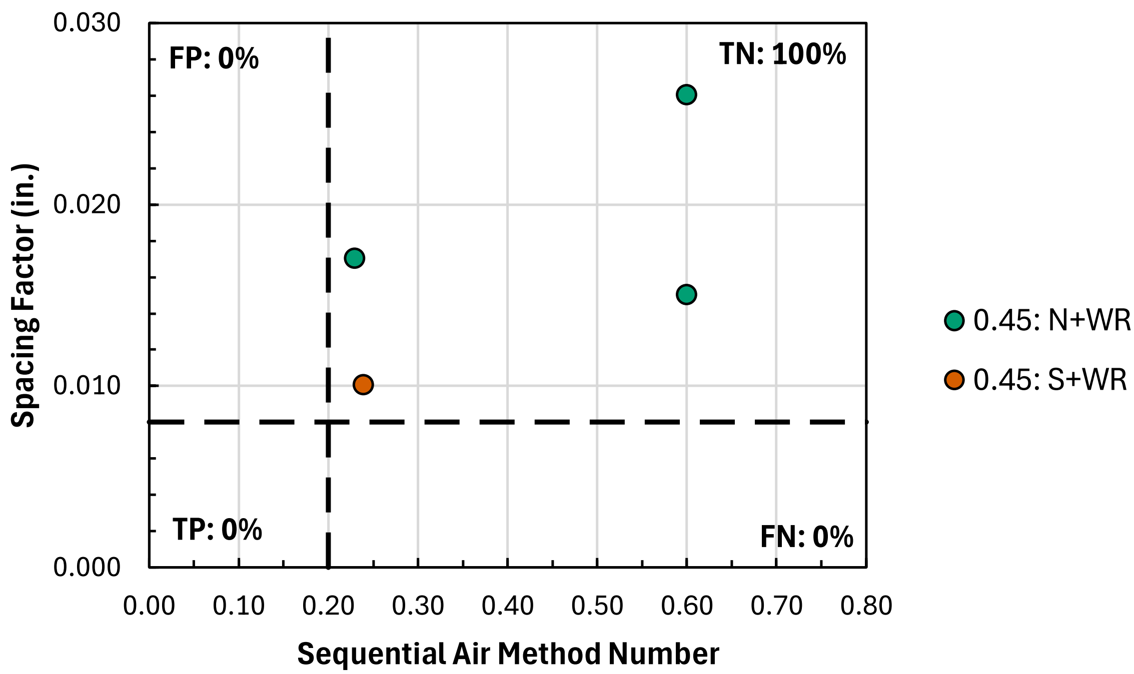


Figure 5-12. Spacing Factor (in.) versus SAM Number data obtained from laboratory testing (n = 4). The vertical line is the recommended maximum SAM number of 0.20, and the horizontal line is the ACI 201.2 (2023) recommended maximum spacing factor of 0.008 in.

As was the case in Section 4.7, the ability of the spacing factor, SAM number, and total air content to predict whether a concrete mixture has a durability factor greater than or less than an acceptable value of 60 is investigated in this section. Figure 5-13 shows durability factor versus spacing factor results and classifications based on a spacing factor threshold of 0.008 inches and a durability factor of 60. The results show that the concrete mixture with a spacing factor of 0.008 inches passed AASHTO T 161 (2022) testing with a durability factor of 69, as expected. Three concrete mixtures with spacing factors in the 0.010 to 0.017 inch range also passed AASHTO T 161 (2022) testing, which suggests that the current ACI 201.2 (2023) recommended limit of 0.008 inches is conservative. This was also the case for Malhotra (1977) who found that some concrete mixtures with spacing factors greater than 0.008 inches had durability factors greater than 90, implying excellent freeze-thaw resistance. Conversely, two concrete mixtures tested in this study with spacing factors of 0.015 and 0.018 inches failed AASHTO T 161 (2022) testing. The reason for this variance in freeze-thaw resistance of concrete mixtures with similar spacing factors is not known.

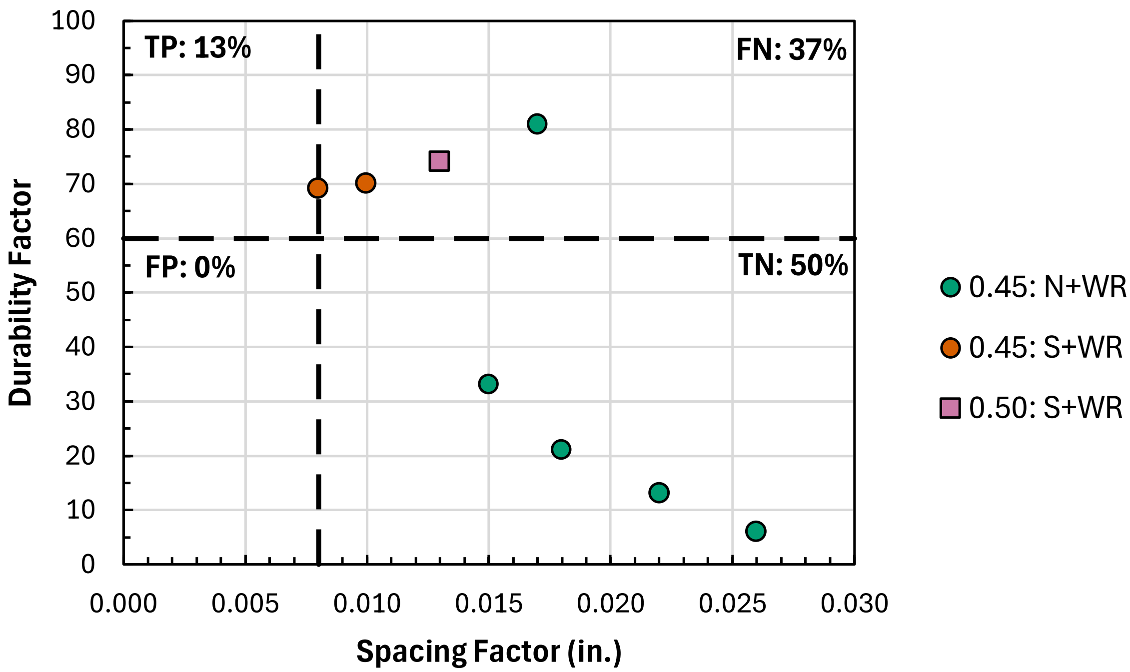


Figure 5-13. Durability Factor versus Spacing Factor (in.) results (n = 8). The vertical line shows the ACI 201.2 (2023) recommended maximum spacing factor of 0.008 in., and the horizontal line shows an acceptable durability factor of 60.

Figure 5-14 shows durability factor versus SAM number results and classifications based on a SAM number of 0.20 and a durability factor of 60. Figure 5-15 shows durability factor versus total air content results and classifications based on the optimized total air content of 3.5% for concrete mixtures without PC HRWR admixture and a durability factor of 60.

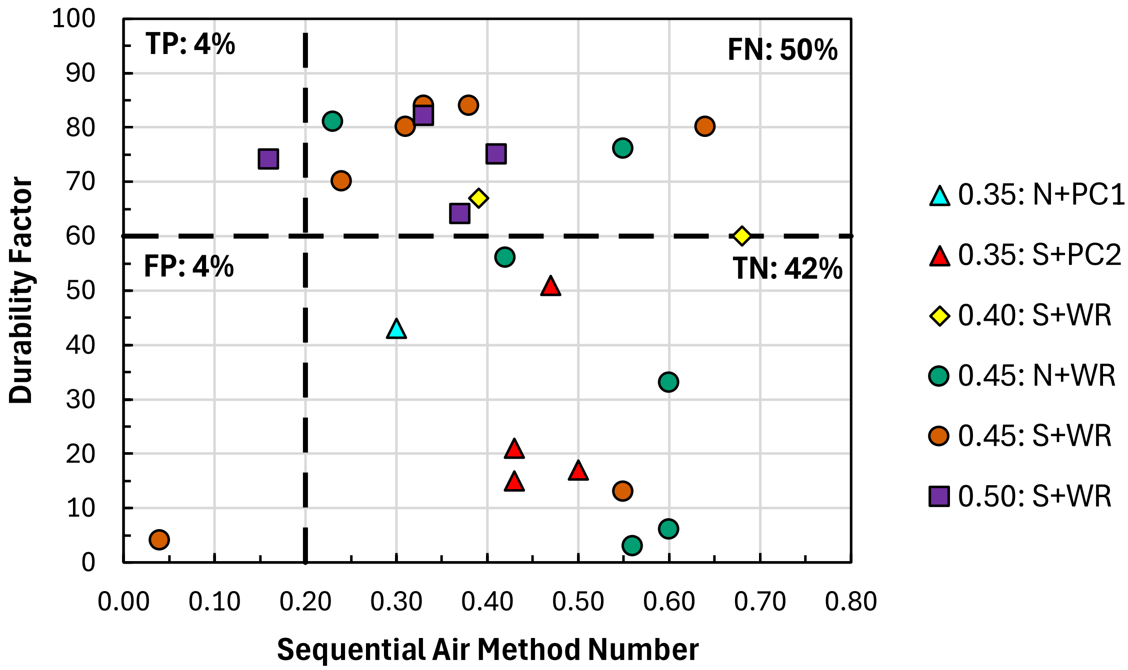


Figure 5-14. Durability Factor versus SAM Number results (n = 24). The vertical line shows the recommended maximum SAM number of 0.20, and the horizontal line shows an acceptable durability factor of 60.

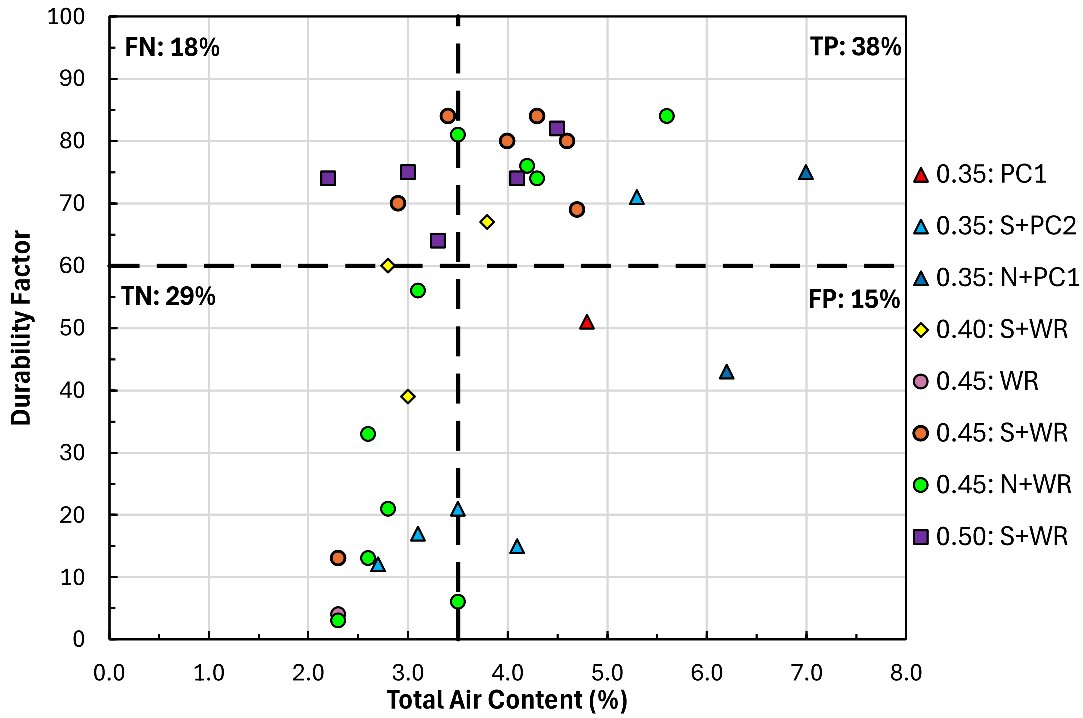


Figure 5-15. Durability Factor versus Total Air Content (%) results (n = 34). The vertical line shows the optimized minimum total air content of 3.5%, and the horizontal line shows an acceptable durability factor of 60.

For ease of comparison, the number of occurrences and percentage of true positive, true negative, false positive, and false negative results for each predictor (spacing factor, SAM number, and total air content) of durability is shown in Table 5-7. Table 5-7 shows that using the thresholds described in this section, the total air content correctly predicts the greatest percentage of durability factor results (68%), while the spacing factor minimizes the occurrence of false positive results at a value of 0%. When comparing the two fresh concrete metrics—the SAM number and the total air content—the SAM number does better to identifying non-freeze-thaw resistant concrete mixtures due to its lower false positive rate (4% compared to 15%). However, as shown in Figure 5-3, when concrete mixtures containing PC HRWR admixture are excluded from the analysis, the false positive rate for the total air content drops to 4%. This is equivalent to the false positive rate for when the SAM number is used and implies that the SAM number and total air content are equally capable of identifying potentially non-durable concrete when PC HRWR admixture is not present.

Table 5-7. Results of Classification Analysis of Data Obtained from Laboratory Testing.

Classification of Durability Factor ≥ 60 by Spacing Factor ≤ 0.008 in.						
	TP	**TN**	**FP**	**FN**	**Correct**	**Total**
Observations (n)	1	4	0	3	5	8
Percent	13	50	0	37	63	
Classification of Durability Factor ≥ 60 by SAM Number ≤ 0.20						
	TP	**TN**	**FP**	**FN**	**Correct**	**Total**
Observations (n)	1	10	1	12	11	24
Percent	4	42	4	50	46	
Classification of Durability Factor ≥ 60 by Total Air Content (%) ≥ 3.5%						
	TP	**TN**	**FP**	**FN**	**Correct**	**Total**
Observations (n)	13	10	5	6	23	34
Percent	38	29	15	18	68	

Note: TP = True Positive, TN = True Negative, FP = False Positive, FN = False Negative

When all concrete mixtures are analyzed for the SAM number results, the 11% reduction in the false positive rate comes with a substantial downside: 50% of results are classified as false negatives, compared to only 18% for the total air content. Practically, this implies that while using the SAM number as a criterion for concrete acceptance reduces the amount of potentially non-durable concrete that is accepted in the field, it also substantially increases the amount of durable concrete that is rejected. This trade-off represents a significant downside for contractors. Not only is achieving a SAM number of 0.20 or less difficult, but there is also a high probability of concrete mixtures that fail the AASHTO T 395 (2024) test with SAM numbers in the 0.21 to 0.35 range getting rejected in the field despite them having potentially acceptable freeze-thaw resistance. This is evidenced by the results in Figure 5-14, which shows that while

54% of the 24 concrete mixtures produced and tested in this study had a durability factor of 60 or greater, only 8% had a SAM number of 0.20 or less.

The results of the analysis of data obtained from literature shown in Table 4-5 and the results obtained from laboratory testing in Table 5-7 generally align with several trends emerging. The total air content threshold of 3.5% is better than the spacing factor threshold of 0.008 inches and the SAM number threshold of 0.20 at correctly predicting whether the durability factor is greater or lesser than 60. The SAM number and total air content exhibit similar capability in limiting the acceptance of non-freeze-thaw resistant concrete in the field to 1 to 4% when PC HRWR admixture is not present. When PC HRWR admixture is present, analysis of laboratory testing data suggests that the false positive rate may be as high as 15%, whereas analysis of data from literature suggests that this number may only be 2%. Looking at false negative rates, far more potentially freeze-thaw resistant concrete mixtures will be rejected if a SAM number of 0.20 is used as a criterion for acceptance compared to if a total air content threshold of 3.5% is used. For the SAM number, the false negative rate is 27% for literature-derived data and 50% for laboratory-testing-derived data. For the total air content, these values are 21 and 18% which are much lower.

5.8 Evaluation of the Sequential Air Method

This subsection discusses the SAM meter's ability to accurately determine the total air content, its ability to provide an indication of a concrete mixture's freeze-thaw resistance, reliability and variability, and operational complexity.

5.8.1. Capability of SAM to Accurately Determine Total Air Content

The ability of the SAM meter to accurately determine the total air content was determined by comparing total air content values obtained using the SAM meter to the total air content values obtained using the Type B Pressure meter in accordance with AASHTO T 152 (2024). These results are shown in Figure 5-16.

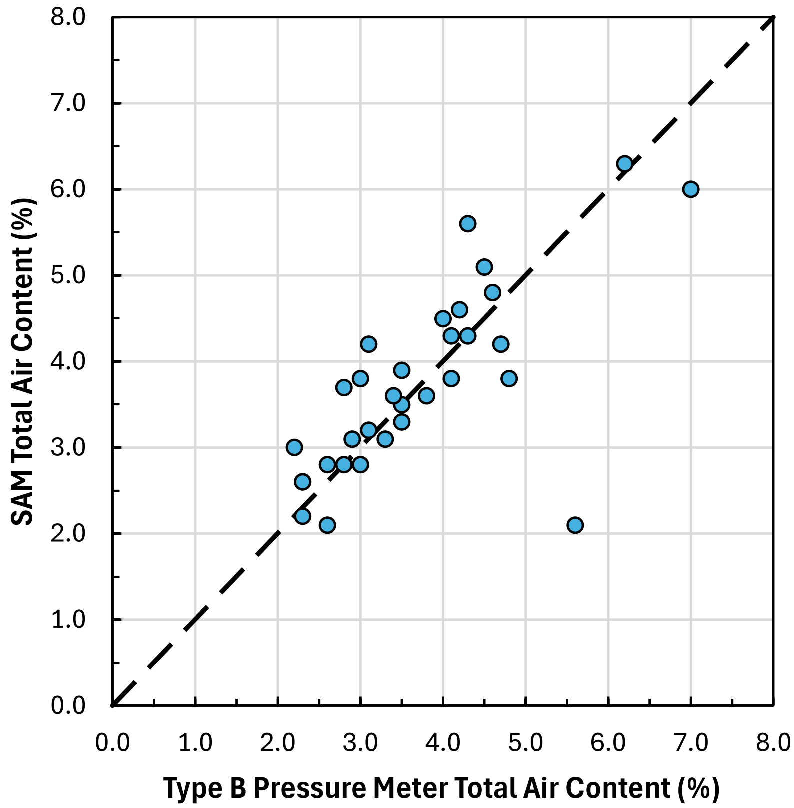


Figure 5-16. SAM Total Air Content versus Type B Pressure Meter Total Air Content (n = 33). The black diagonal line represents the case in which the SAM Total Air Content matches the Type B Pressure Meter Total Air Content.

The average absolute difference between the SAM meter and the Type B pressure meter total air contents was 0.5%, while the average difference was 0.0%. This indicates that a random

SAM meter total air content is likely to differ from a Type B pressure meter total air content by +/- 0.5%, but the average of all the differences between the two total air content measurements is 0.0%. Table 5-8, adapted from Table 1 of AASHTO T 152 (2024), shows the acceptable difference between two total air content results obtained using the Type B pressure meter. The table shows that the acceptable difference between results varies with the total air content obtained from the test.

Table 5-8. Indexes of Precision for Air Contents between 3 and 8 Percent[1]

(Adapted from AASHTO T 152 (2024))

Total Air Content (%)	**Single-Operator Precision**
	Acceptable Difference between Two Results (%)[2]
3	0.33
4	0.44
5	0.55
6	0.66
7	0.77
8	0.88

Note 1: Use interpolation to determine precision values for total air contents between the values given in the table.
Note 2: These numbers represent the difference limits (d2s) as described in ASTM C670 (2024).

The average absolute difference between two results of 0.5% is slightly greater than the acceptable difference between two total air content results found using the Type B pressure meter for total air contents of 3.0 to 4.6% but is less than the acceptable difference for all other total air contents. In other words, for total air contents of 4.7% or greater, the average absolute difference between results of 0.5% is less than the acceptable difference between two results. If the outlier pair of total air contents (5.6% from the Type B pressure meter and 2.1% from the SAM meter) is removed, the average absolute difference between two results is 0.41%. This is still slightly greater than the acceptable difference for total air contents of 3.0 to 3.6%, which varies from 0.33 to 0.40% but less than the acceptable difference for all other total air contents. These results imply that while the average total air content obtained using the SAM meter is similar to the total air content obtained from the Type B pressure meter, the average absolute difference between the two total air contents when the total air content is less than 3.6% can be greater than the acceptable difference between two results obtained using the Type B pressure meter.

5.8.2. Durability Factor Prediction Capacity of the SAM

As was discussed in Section 5.7 and shown in Table 5-7, a SAM number of 0.20, as was recommended by Ley et al. (2017), is only able to correctly predict whether a concrete mixture's durability factor will be greater or lesser than 60 for 46% percent of results. This is significantly less than a total air content of 3.5%, which has a correct prediction rate of 68%. Regarding minimizing the false positive rate, or practically speaking, the rate at which non-freeze-thaw resistant concrete is placed and accepted in the field, using a SAM number of 0.20 results in a false positive rate of 4%, while using a total air content of 3.5% results in a false positive rate of 15%. Therefore, using a SAM number of 0.20 as opposed to a total air content of 3.5% as an acceptance criterion causes the number of false positive results to decrease by 11%. While this is a significant improvement, it is based on a limited dataset of only 24 durability factor versus SAM number results and 34 durability factor versus total air content results obtained from this study's laboratory testing. When examining the difference in the false positive rates based on a larger data set, this difference decreases significantly. The meta-analysis of literature-derived data found that the difference in the false positive rates using the SAM number and the total air content was only 1%. This difference, shown in Table 4-5, is based on 77 durability factor versus SAM number results and 391 durability factor versus total air content results.

The limited improvement in the false positive rate when using the SAM number as opposed to the total air content comes with the significant downside of a substantially higher false negative rate. This means that rejecting concrete mixtures based on their SAM number results in many more freeze-thaw resistant concrete mixtures getting rejected in the field. For instance, the analysis of data obtained from literature described in Section 4.7 found that the false positive rate based on the SAM number was 27% compared to the reduced false positive rate based on the total air content of 21%. This finding is also true of data obtained from this study's laboratory testing, which found that the false positive rates are 50% for the SAM number and 18% for the total air content. Therefore, it can be concluded that using the SAM number as a criterion for concrete acceptance as opposed to the total air content results in a marginal benefit for ALDOT and a substantial drawback for contractors.

5.8.3. Reliability and Variability

The reliability of the SAM meter and the variability of the SAM number were also investigated. Of the 32 times the SAM meter was used, it was only successful 25 times in showing the SAM number. The difference in SAM results is because it shows "error" on its output display, and no SAM number is reported. This means that the SAM meter reported an error 22% of the time the AASHTO T 395 (2024) test was run. In instances in which the SAM meter reports an error, the AASHTO T 395 (2024) test would either have to be rerun, or the total air content would have to be relied upon as an indicator of durability instead of the SAM number. This high rate of SAM errors indicates that the SAM meter is an unreliable apparatus for determining concrete durability when compared to a Type B pressure meter.

The SAM number is also highly variable when compared to the total air content determined from both the SAM meter and the Type B pressure meter. Figure 5-17 is a box and whisker plot showing the statistics regarding the percentage difference in consecutive test results for the total air content determined from the Type B pressure meter, the total air content determined from the SAM meter, and the SAM number obtained from the SAM meter. The black line in the middle of each box indicates the median difference, the X indicates the mean difference, the top and bottom of the box indicate the upper (75%) and lower (25%) quartiles of the difference, the whiskers indicate differences that are within 1.5 times the inner quartile range (IQR) above and below the top and bottom of the IQR, and the dots represent outliers. The figure shows that the IQR of differences in consecutive SAM number results is significantly greater than that of both total air content results, thus indicating that consecutive SAM number results are far more variable than consecutive total air content results. This is true when one outlier difference between consecutive SAM results of 750% is both included (green box) and excluded (pink box) in the analysis. The figure also indicates that absolute mean difference of 39% between consecutive SAM number results is far greater than the absolute mean difference of 17 to 19% between consecutive total air content results. More detailed variability analysis results can be found in Table 5-9.

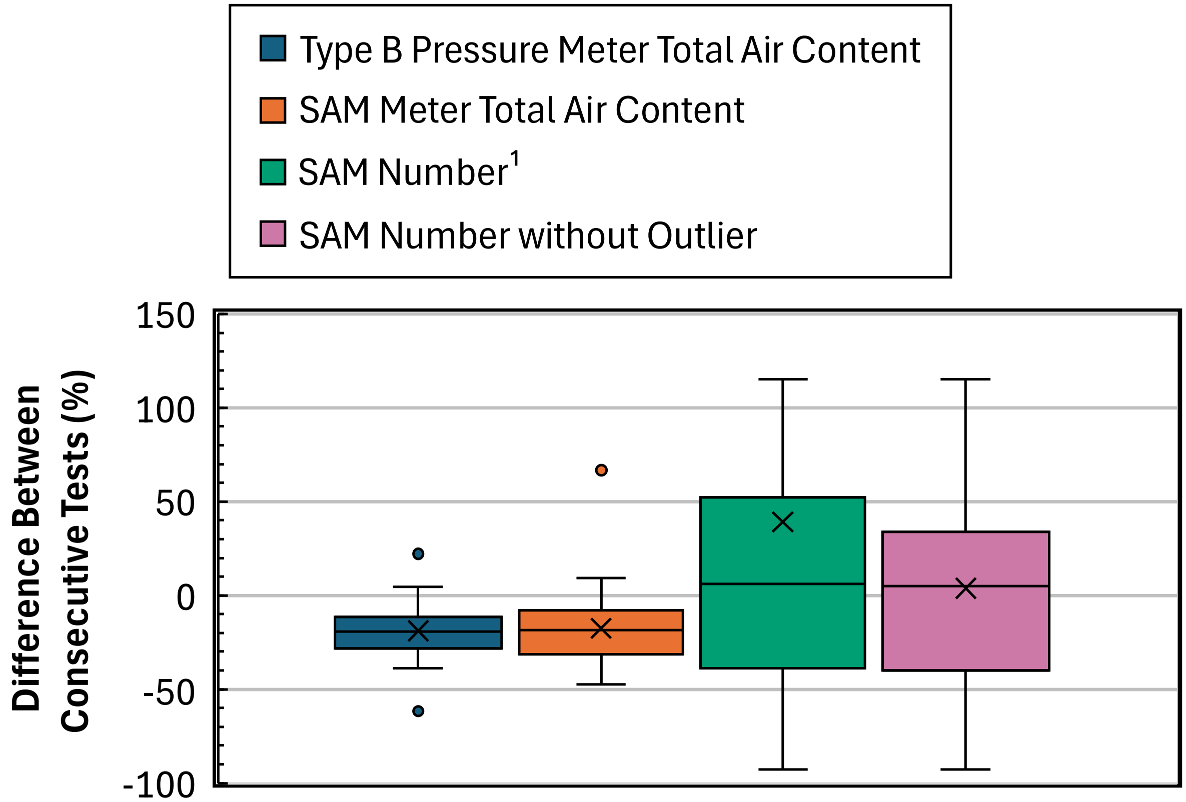


Figure 5-17. Percentage difference between consecutive test results for the total air content obtained from both the Type B Pressure Meter and the SAM meter and the SAM number obtained from the SAM meter.

Note 1: One SAM number percent difference, 750%, is excluded from this figure for readability purposes.

Table 5-9. Variability of Differences Between Two Consecutive Test Results.

	Type B Pressure Meter Total Air Content	SAM Meter Total Air Content	SAM Number[1]	SAM Number without Outlier
Mean (%)	-18.9	-17.4	39.3	3.7
Median (%)	-19.2	-18.6	6.0	5.1
Standard Deviation (%)	15.8	21.9	173.4	61.0
IQR (%)	17.0	23.5	91.1	73.9
Q3 (3rd quartile) (%)	-11.3	-7.9	52.4	34.0
Q1 (1st quartile) (%)	-28.2	-31.3	-38.7	-39.9

Note 1: Numbers in SAM Number column include outlier result of 750%.

The results in Table 5-9 indicate that the variability between consecutive total air content results is very similar regardless of whether a Type B pressure meter or a SAM meter is used to determine the total air content. The negative 17 to 19% mean and median differences between the first and second total air content results suggest that concrete mixtures made in this study consistently lost a moderate portion of air between the first and second total air content measurements. This apparent reduction in air resulted in a large mean increase in the SAM number of 39% but only a median difference in the SAM number of 6%. Despite the median difference between consecutive SAM number results being only 6%, the standard deviation and IQR were far greater for SAM number results than for total air content results. When the outlier percent difference between consecutive SAM tests of 750% is excluded from the analysis, the mean and median differences decrease to 3.7 and 5.1%, respectively. These are less than those of the total air content obtained from both the Type B pressure meter and the SAM meter. However, the IQR and upper (75%) and lower (25%) quartiles are still greater for the SAM than for the total air content. Practically speaking, the substantially greater variability of SAM number means that if an AASHTO T 395 (2024) test results needs to be reperformed, the likelihood of obtaining a substantially different result than the first test result is very high.

5.8.4. SAM Meter Operational Complexity

Another factor the research team considered when evaluating the SAM meter is its operational complexity. As discussed in Section 3.6.1, there are 26 steps that are required to be completed to successfully conduct an AASHTO T 395 (2024) test. This is substantially more than the six steps required to successfully complete an AASHTO T 152 (2024) test using the Type B pressure meter. Because 20 extra steps are required, this results in an AASHTO T 395 (2024) test taking substantially longer than an AASHTO T 152 test. The research team found that it took on average approximately 14 minutes to conduct an AASHTO T 395 (2024) test, while it only took approximately 4 minutes to conduct a total air content test. Additionally, because extra steps were required for the AASHTO T 395 (2024) test, it took the test operators longer to fully master the steps than it did for the total air content test. If the SAM number was required as an acceptance criterion for ALDOT concrete structures, it would result in many technicians needing to be thoroughly trained on how to use the SAM meter, and this would still not prevent the SAM from showing “error” as an output. Training of technicians would also be an additional expense for ALDOT and contractors.

The research team also found it difficult to stay within the stringent pressure tolerance of +/- 0.05 psi required in AASHTO T 395 (2024) during the sequential pressurization steps at the 14.5, 30.0, and 45.0 psi steps. Achieving pressures within this tolerance consistently proved to be challenging, as over and under-pressurizing the top chamber at these pressure steps was common, thus necessitating frequent pressure adjustments that slowed down the test. When a pressure imbalance occurred between two sequential pressurization runs, the SAM meter sometimes generated an error, rendering that test invalid and necessitating a retest on another concrete sample. Therefore, an extreme level of care needed to be taken to achieve nearly equal pressures in sequential pressurization runs to prevent errors. This high amount of care devoted to achieving nearly equal pressures was also a major contributing factor to the extended 14-minute duration of the AASHTO T 395 (2024) test.

5.8.5. Comparison of the SAM Meter to the Total Air Content using the Type B Pressure Meter

This subsection summarizes the findings discussed in the previous subsections of Section 5.8. It compares the identification capacity of the SAM number and the total air content in addition to comparing the performance of the SAM meter to Type B pressure meter. These comparisons are summarized in Table 5-10.

Table 5-10. Comparison of AASHTO T 152 (2024) and AASHTO T 395 (2024).

Metric	**Test Method**	
	Type B Pressure Meter (AASHTO T 152 2024)	**SAM Meter (AASHTO T 395 2024)**
Durability Factor Prediction Capacity	Moderately High	Moderate
False Positive Minimization	Very Good to Excellent	Excellent
False Negative Minimization	Moderate	Poor
Reliability of Test Apparatus	Excellent	Poor
Variability of Test Results	Moderate	Very High
Operational Complexity	Minimal	High

Overall, the research team found that the SAM number provides only marginal benefit in preventing the placement and acceptance of potentially non-freeze-thaw resistant concrete mixtures when compared to using only the total air content. The research team also found that the total air content has a better capacity to predict a concrete mixture's durability factor and does better to minimize the number of potentially freeze-thaw resistant concrete mixtures that may be rejected in the field. This finding is especially true of concrete mixtures that do not contain PC HRWR admixture. Moreover, the team found the SAM meter to be unreliable, time-consuming to operate, and difficult to operate. These downsides are in addition to the fact that the differences between results of consecutive SAM (AASHTO T 395 2024) tests are highly variable when compared to the differences between consecutive total air content results. Given the downsides of the sequential air method (AASHTO T 395 2024) discussed in this section, the use of the SAM number for concrete mixture acceptance is not recommended for implementation by ALDOT.

5.9 Influence of Water-to-Cement Ratio, Strength, and Type of Air-Entraining Admixture on Freeze-Thaw Resistance

5.9.1. Influence of Water-to-Cement Ratio on Freeze-Thaw Resistance

To visually isolate the influence of w/cm, Figure 5-18 shows the durability factor versus w/cm of all concrete mixtures tested. The figure shows no correlation between w/cm and durability factor as wide ranges in the durability factor for each w/cm are present. For instance, the durability factor range of the 0.45 w/cm concrete mixtures is 3 to 84. This suggests that the quality of the air-void system, quantified by the spacing factor and number of voids smaller than

200 micrometers per inch as discussed in Section [xyz], is far more important in ensuring a concrete mixture is freeze-thaw resistant than the w/cm. This supports findings discussed in Section 4.10 and those of Felice, Freeman, and Ley (2014) and Tanesi and Meininger (2006) who also reached the same conclusion.

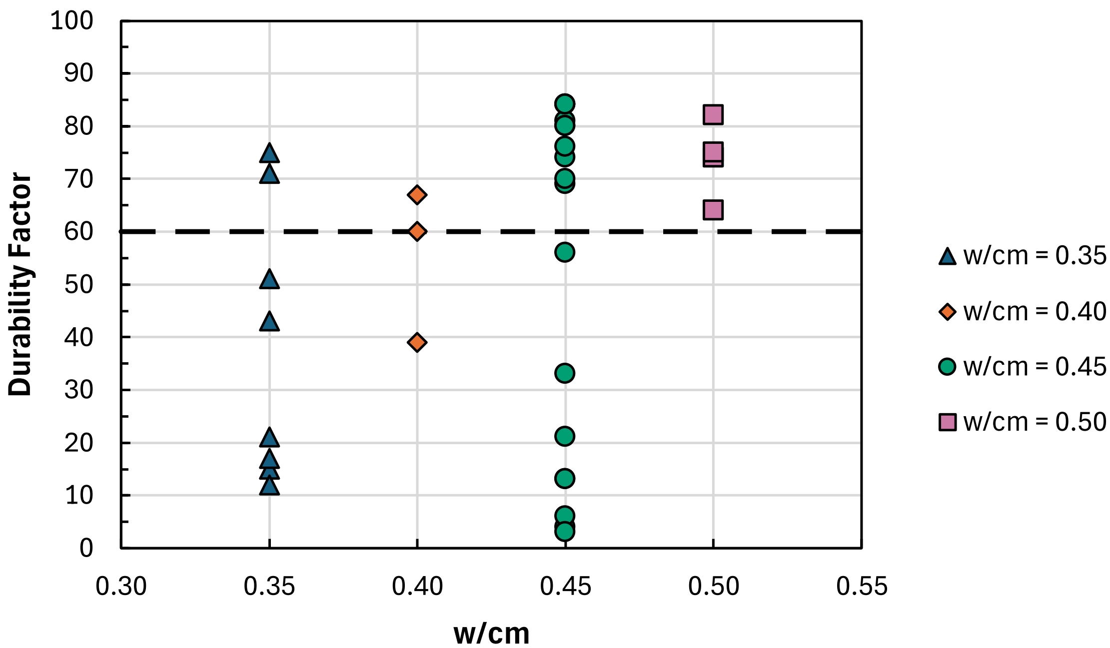


Figure 5-18. Durability factor versus w/cm results of all concrete mixtures tested in the laboratory (n = 34).

5.9.2. Influence of Strength on Freeze-Thaw Resistance

ACI Code 318-25, *Building Code for Structural Concrete—Code Requirements and Commentary* (ACI Committee 318 2025) includes a provision in Section 19.3.3.6 that states that when the compressive strength is greater than or equal to 5000 psi, the required total air content indicated in Table 19.3.3.1 and 19.3.3.3 of ACI 318-25 may be reduced by 1.0%. Therefore, the research team investigated the influence of concrete strength on freeze-thaw resistance to determine if the inclusion of this provision was appropriate and if such a provision would be appropriate for ALDOT structures. Figure 5-19 and Figure 5-20 show the relationships between the durability factor and the 28-day and 56-day compressive strengths, respectively. No clear relationship between compressive strength and the durability factor is observable. This supports the finding of Lomboy and Wang (2009) who found no relationship exists between compressive strength and durability factor for air-entrained concrete. Therefore, it is not recommended to allow for a reduction in the total air content requirement in ALDOT's specification for concrete mixtures that have a certain compressive strength.

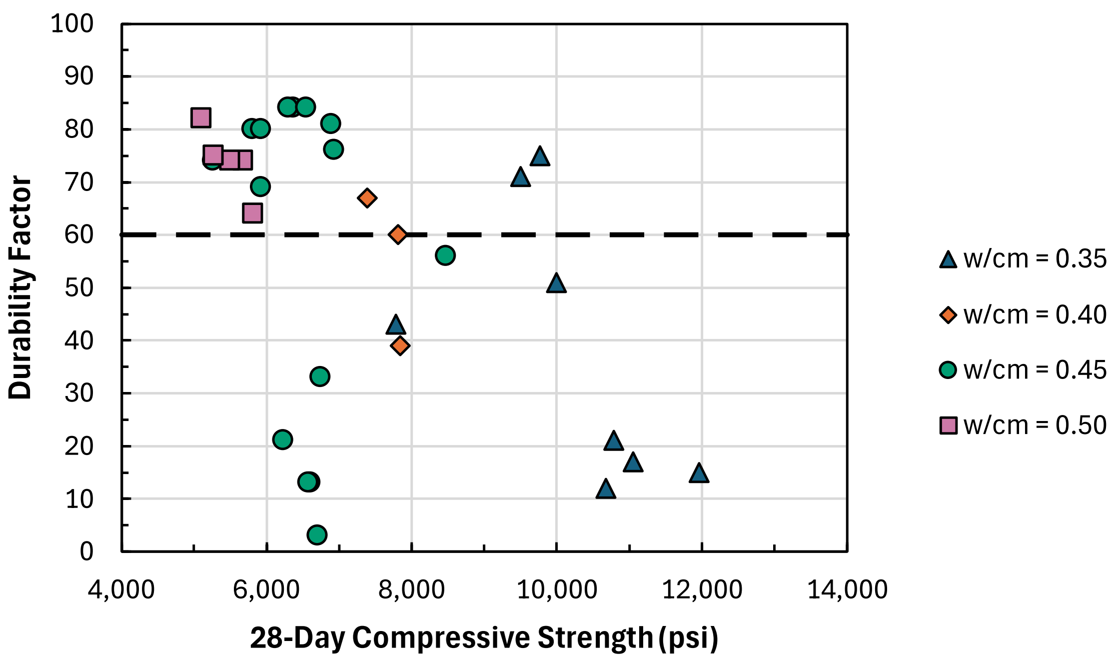


Figure 5-19. Durability factor versus 28-day compressive strength results for concrete mixtures tested in the laboratory (n = 34).

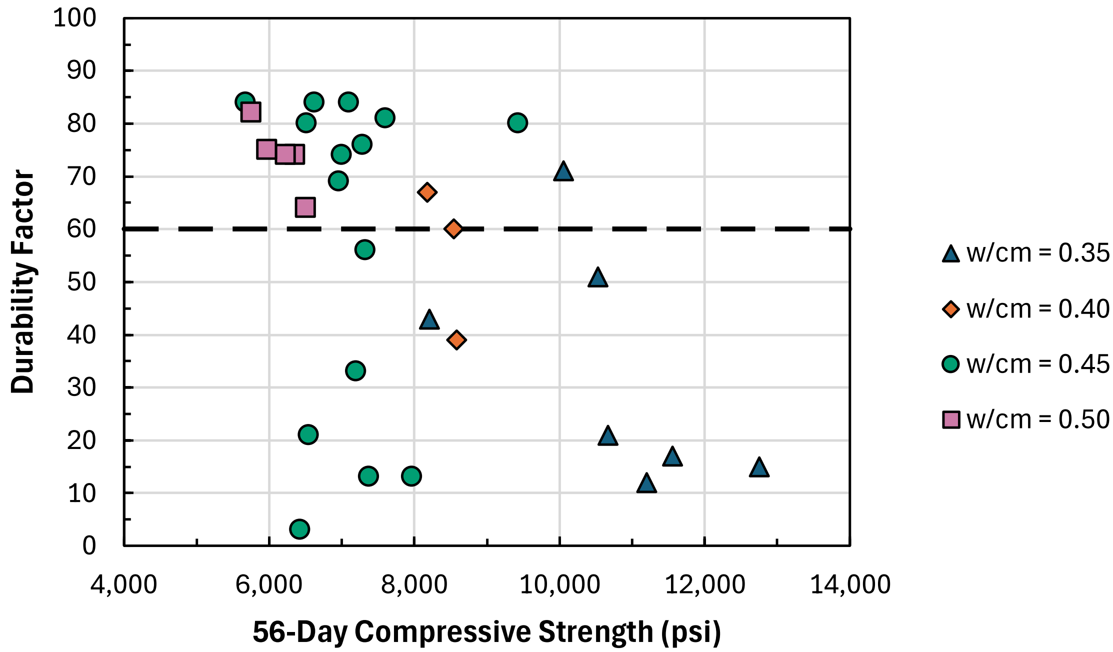


Figure 5-20. Durability factor versus 56-day compressive strength results for concrete mixtures tested in the laboratory (n = 33).

5.9.3. Influence of Type of Air-Entraining Admixture on Freeze-Thaw Resistance

Figure 5-21 shows durability factor versus total air content results for concrete mixtures with w/cm=0.45 made with natural and synthetic air-entraining admixtures. Results for other w/cm were not included in the figure so that the effect of the air-entraining admixture type could be examined in isolation without the influence of other factors such as w/cm and type of water reducing admixture. The results show that concrete mixtures with similar total air contents perform similarly, regardless of whether they were made with synthetic or natural air-entraining admixture. This supports the inconclusive results found in Section 4.8.3, which showed that no statistically significant improvement in durability was observed in concrete mixtures made with synthetic air-entraining admixtures as opposed to natural air-entraining admixtures.

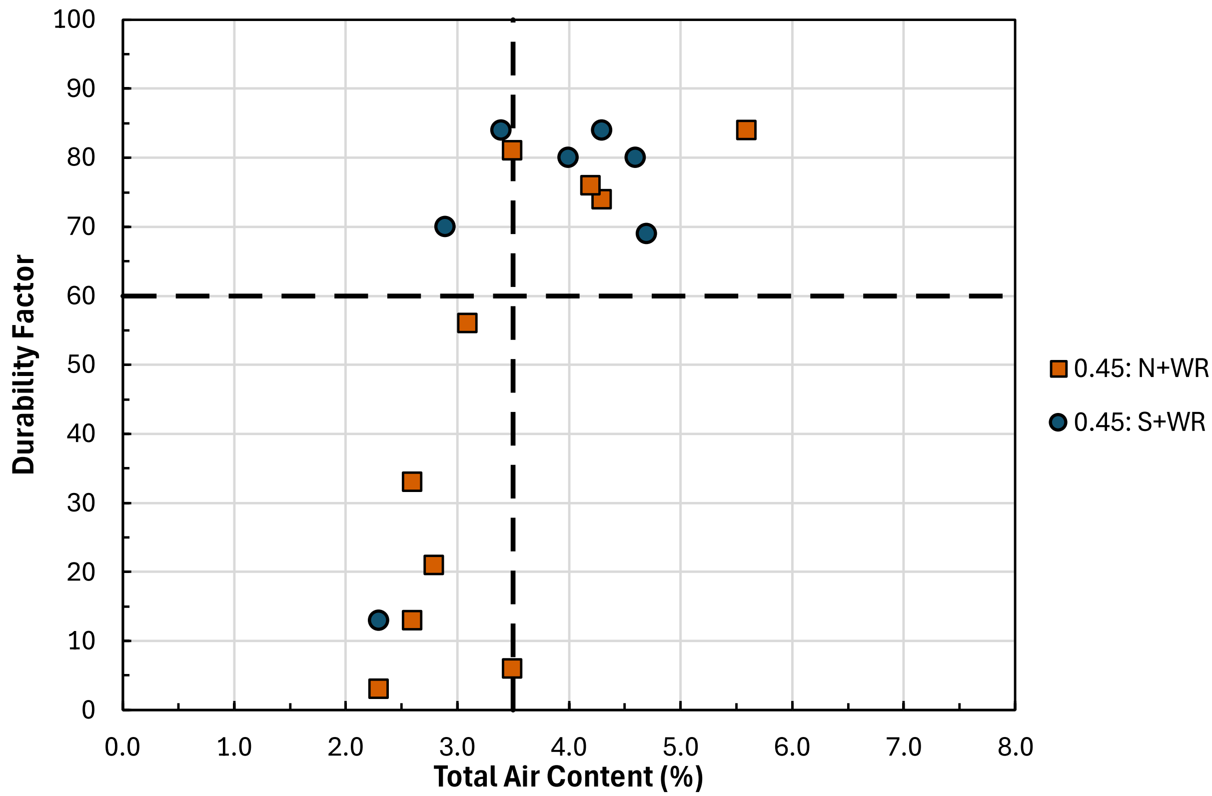


Figure 5-21. Durability factor versus total air content results for concrete mixtures with w/cm=0.45 made with natural and synthetic air-entraining admixtures (n=17).

5.10 Summary

In this chapter, data collected from laboratory testing was analyzed and discussed to establish a minimum total air content threshold for target durability factors of 60 and 80. Relationships between indicators of durability were established, and the SAM meter was evaluated for potential use in ALDOT projects. Potential factors that impact concrete freeze-thaw resistance including the w/cm, strength, and type of chemical admixture were also analyzed.

The key findings of the analysis of laboratory testing data performed in this chapter are as follows:

- For concrete mixtures without PC HRWR admixture, the optimal total air content threshold for a target durability factor of 60 is 3.5%. This results in a false positive rate of 4% and a false negative rate of 23%.
- For concrete mixtures without PC HRWR admixture, the optimal total air content threshold for a target durability factor of 80 is 4.0%. This results in a false positive rate of 15% and a false negative rate of 8%.
- For concrete mixtures containing PC HRWR admixture, there does not appear to be an optimal total air content threshold. For concrete mixtures made with synthetic air-entraining admixtures and PC2, a total air content of at least 5.0% is required for them to achieve an acceptable durability factor of at least 60. For mixtures made with natural air-entraining admixtures and PC1, this value appears to be 7.0%.
- The following thresholds are able to identify concrete mixtures with durability factors of 60 or greater at the following rates:
    - A total air content threshold of 3.5%: 67% correct identification with a false positive rate of 15%.
    - A SAM number threshold of 0.20: 46% correct identification with a false positive rate of 4%.
    - A spacing factor threshold of 0.008 inches: 63% correct identification with a false positive rate of 0%.

- Of the thresholds evaluated, the total air content threshold of 3.5% is able to correctly predict a concrete mixture's durability factor with the greatest accuracy.
- Based on the SAM number results obtained using the SAM meter, the SAM number only performs marginally better than the total air content at minimizing the false positive rate of durability factor results. Consecutive SAM number results of consecutive AASHTO T 395 (2024) tests were highly variable when compared to consecutive total air content results. The SAM meter also reported an error in 22% of tests.
- The use of the SAM number for concrete mixture acceptance is not recommended for implementation by ALDOT.
- The research team found that the AASHTO T 395 (2024) test took longer to learn and longer to perform than the AASHTO T 152 (2024) test. It was also found achieving the pressure steps of 14.5, 30.0, and 45.0 +/- 0.05 psi was challenging and time consuming.
- No relationships were found between concrete freeze-thaw resistance and w/cm, strength, or type of air-entraining admixture.

CHAPTER 6

PROPOSED IMPLEMENTATION OF RESEARCH RESULTS

6.1 Proposed Implementation Recommendations

This chapter includes recommended ways in which the findings of this research can be implemented by ALDOT. These include updating the minimum required total air content and the total air content range for ALDOT concrete mixtures and continuing to use the Type B pressure meter for quality assurance testing.

6.1.1. Minimum Required Total Air Content and Total Air Content Range

Based on the finding of Sections 4.4 and 5.4 that the optimized total air content for a target durability factor of 60 is 3.5%, it is recommended to increase the minimum required total air content to 3.5% statewide. Doing so would significantly reduce the amount of potentially non-freeze-thaw durable concrete that is placed, a measure that could substantially improve the long-term freeze-thaw durability of Alabama's newly constructed concrete infrastructure. Increasing ALDOT Section 501's minimum required total air content for concrete classes A through D to 3.5% aligns well with specifications of surrounding states, as shown in Figure 6-1, an updated version of Figure 2-3. In this scenario, ALDOT's minimum required total air content would be 0.5% greater than Mississippi's, the same as Georgia's, and 0.5% less than Arkansas' and South Carolina's. This is logical since Alabama has a similar climate to those states, and therefore its concrete infrastructure is exposed to a similar number of cycles of freezing and thawing. While the primary focus of this research has been on ALDOT 501 concrete mixtures, for consistency and improved performance, this minimum total air content should also be used in ALDOT 450 that covers concrete pavements. This is because concrete pavements are exposed to the same moisture conditions and the same number of freeze-thaw cycles as ALDOT 501 concrete mixtures, meaning that the required level of freeze-thaw protection should be the same.

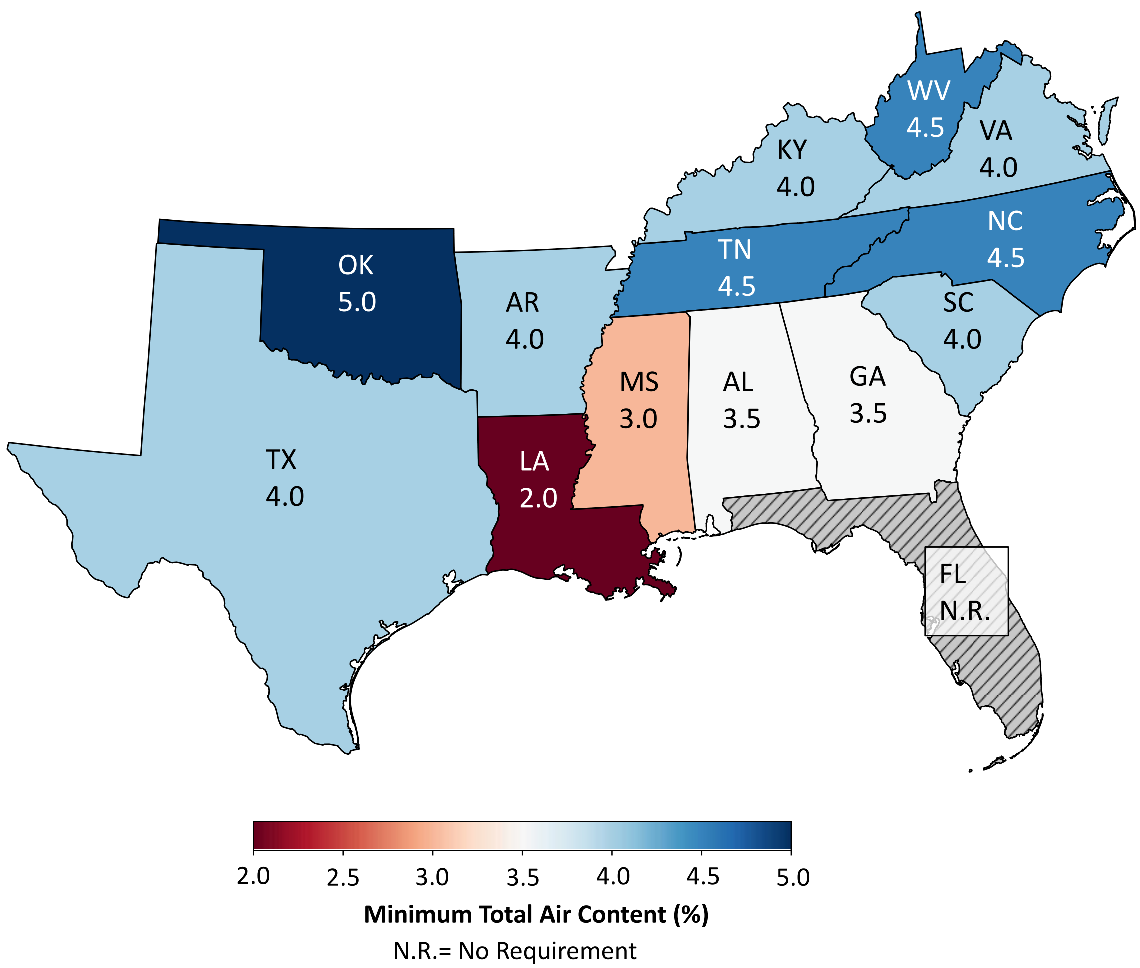


Figure 6-1. Updated Minimum Total Air Contents of Bridge Deck Concrete Specified by State DOTs of SASHTO Member States.

Given that it is recommended to increase the minimum required total air content by 1.0%, it also recommended to increase the maximum permissible total air content by 1.0%. This preserves the current total air content range of 3.5% which provides concrete producers with a buffer to produce air-entrained concrete within the total air content range of 3.5 to 7.0%. The current and recommended total air content ranges for ALDOT classes A through D concrete mixtures are displayed in Table 6-1.

Table 6-1. Current and Recommended Total Air Content Ranges for ALDOT 501 Concrete Mixtures.

Range	Minimum Total Air Content (%)	Maximum Total Air Content (%)
Current ALDOT 501	2.5	6.0
Current ALDOT 450	2.0	6.0
Recommended	3.5	7.0

6.1.2. Continued Use of the Type B Pressure Meter

The Type B pressure meter (AASHTO T 152 2024) and SAM (AASHTO T 395 2024) were both evaluated for use in ALDOT projects in this research. AASHTO T 152 (2024) is recommended for continued use for quality assurance testing for the following reasons:

- The Type B pressure meter (AASHTO T 152 2024) can successfully identify the majority of non-freeze-thaw resistant concrete mixtures. In laboratory testing of concrete mixtures without PC HRWR admixture, only 4% of results were false positives when a minimum total air content threshold of 3.5% was used for a target durability factor of 60.
- The Type B pressure meter (AASHTO T 152 2024) is a reliable test apparatus with the research team determining the total air content for 100% of concrete mixtures tested in laboratory testing.

- Current concrete technicians have already been trained and certified to use the Type B pressure meter (AASHTO T 152 2024) and therefore require no further training for continued use of the Type B pressure meter.

The Sequential Air Method (AASHTO T 395 2024) is not recommended for use in ALDOT projects for the following reasons:

- There is no significant difference in the ability of the SAM (AASHTO T 395 2024) to identify non-freeze-thaw resistant concrete mixtures compared to that of AASHTO T 152 (2024). In the analysis of data obtained from literature, it was found that 1% of results were false positives when a maximum SAM number of 0.20 was used as an acceptance criterion compared to 2% of results being false false positives when a minimum total air content of 3.5% was used as an acceptance criterion.
- The SAM meter performed unreliably, with it producing a SAM number only 78% of the time in laboratory testing.
- Consecutive SAM (AASHTO T 395 2024) test results were highly variable compared to consecutive Type B pressure meter (AASHTO T 152 2024) test results obtained from laboratory testing. The interquartile range of percent differences between consecutive SAM (AASHTO T 395 2024) results was 91% compared to 17% for consecutive Type B pressure meter (AASHTO T 152 2024) results.
- The SAM (AASHTO T 395 2024) is significantly more complex and time-consuming to perform compared to using the Type B pressure meter in accordance with AASHTO T 152 (2024). The SAM (AASHTO T 395 2024) requires 26 steps to complete and takes

approximately 14 minutes on average. Using the Type B pressure meter in accordance with AASHTO T 152 (2024) requires only 6 steps to complete and takes approximately 4 minutes on average to complete.

CHAPTER 7

SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

7.1 Summary

The research in this study consisted of three phases: a literature review, a meta-analysis of literature-derived data, and a laboratory testing program. The literature review was performed to understand the following:

- The theories of the mechanisms causing freeze-thaw damage,
- The prerequisites that must be met for freeze-thaw damage to occur,
- The role of air-entrainment and total air content in freeze-thaw durability,
- Indicators of freeze-thaw durability,
- Other factors affecting freeze-thaw durability,
- Current freeze-thaw durability guidance from state highway specifications, AASHTO specifications and practice, and ACI Code-318 (2025).

In the meta-analysis of literature-derived data, 391 sets of concrete testing results from six literature sources were analyzed using multivariable linear regression analysis, logistic regression analysis, and classification analysis. An optimized total air content to achieve or exceed a durability factor of 60 was determined. The author defines the optimized total air content as the total air content that achieves the dual objectives of minimizing the volume of potentially non-freeze-thaw durable concrete that is placed while minimizing the volume of freeze-thaw durable concrete that is rejected in the field. Relationships between indicators of freeze-thaw durability and the durability factor were also evaluated and discussed.

The laboratory testing phase of the research consisted of testing concrete mixtures with water-to-cementing materials ratios (w/cm) of 0.35, 0.40, 0.45, and 0.50 with total air contents in the 2.0 to 7.0% range. Concrete mixtures were subjected to AASHTO T 152 (2024) testing to determine their total air content, AASHTO T 395 (2024) testing to determine their Sequential Air Meter (SAM) number, and AASHTO T 161 (2022) testing to determine their durability factor. Other quality assurance tests were performed to determine the temperature, slump, unit weight, and compressive strength of the concrete mixtures produced.

7.2 Conclusions

7.2.1. Total Air Content Optimization for Target Durability Factors of 60 and 80

- For concrete mixtures without PC HRWR admixture, the optimal total air content threshold for a target durability factor of 60 is 3.5%. Based on the analysis of literature-derived data, this results in a false positive rate of 2% and a false negative rate of 21%. Similarly, based on the analysis of laboratory test results of mixtures without PC HRWR admixture, the use of 3.5% as the minimum total air content results in a false positive rate of 4% and a false negative rate of 23%.
- Based on the analysis of literature-derived data, for a target durability factor of 60 the false positive rate is 17% and the false negative rate is 9% when using the current ALDOT total air content threshold of 2.5%. Moreover, based on the analysis of laboratory test results of mixtures without PC HRWR admixture, this results in a false positive rate of 23% and a false negative rate of 4%. Therefore, the percentage of false positive results is much lower when a minimum total air content of 3.5% is used

as an acceptance criterion compared to when 2.5% is used as an acceptance criterion.

- For concrete mixtures without PC HRWR admixture, the optimal total air content threshold for a target durability factor of 80 is also 3.5%. For the literature-derived data, this results in a false positive rate of 4% and a false negative rate of 13%. Based on the laboratory testing data of mixtures without PC HRWR admixture, this results in a false positive rate of 22% and a false negative rate of 4%.

7.2.2. Comparison of the Abilities of the Total Air Content, Spacing Factor, and SAM Number to Identify Concrete Mixtures with a Durability Factor of 60 or Greater

- Based on literature-derived data, the following thresholds are able to identify concrete mixtures with durability factors of 60 or greater in accordance with AASHTO T 161 (2022) at the following rates:
    - A total air content threshold of 3.5%: 77% correct identification with a false positive rate of 2%.
    - A SAM number threshold of 0.20: 71% correct identification with a false positive rate of 1%.
    - A spacing factor threshold of 0.008 inches: 62% correct identification with a false positive rate of 2%.
- Based on the literature-derived data, the total air content, spacing factor, and SAM number have nearly equal capability to identify potentially non-freeze-thaw resistant concrete mixtures.

- Based on laboratory testing data, the following thresholds are able to identify concrete mixtures with durability factors of 60 or greater at the following rates:
    - A total air content threshold of 3.5%: 67% correct identification with a false positive rate of 15%.
    - A SAM number threshold of 0.20: 46% correct identification with a false positive rate of 4%.
    - A spacing factor threshold of 0.008 inches: 63% correct identification with a false positive rate of 0%.
- Based on both literature-derived data and laboratory testing results, when considering the total air content threshold of 3.5%, the spacing factor threshold of 0.008 inches, and the SAM number threshold of 0.20, the total air content threshold of 3.5% is able to correctly predict a concrete mixture's durability factor with the greatest accuracy.

7.2.3. Ability of Total Air Content and SAM Number to Predict Spacing Factor

- Based on the analysis of literature-derived data, A SAM number threshold of 0.20 is able to identify concrete mixtures with a spacing factor of 0.008 inches or less 89%, of the time with a false positive rate of 11%. This is better than a total air content threshold of 3.5% which is able to identify concrete mixtures with a spacing factor of 0.008 inches or less 77% of the time with a false positive rate of 20%.
- Based on the analysis of laboratory testing data, a SAM number threshold of 0.20 is able to identify concrete mixtures with a spacing factor of 0.008 inches or less 100% of the time with a false positive rate of 0%. This is better than a total air content

threshold of 3.5% which is able to identify concrete mixtures with a spacing factor of 0.008 inches or less 75% of the time with a false positive rate of 25%.

- Both the literature-derived and laboratory testing phase data suggest that the SAM number is better able to identify concrete mixtures with spacing factors that are 0.008 inches or less.

7.2.4. Evaluation of the Sequential Air Method (SAM)

Conclusions regarding the Sequential Air Method (SAM) (AASHTO T 395 2024) are as follows:

- As discussed in Section 7.2.2, the total air content and SAM number have a comparable ability to identify non-freeze-thaw durable concrete mixtures.
- The SAM meter performed unreliably, with it producing a SAM number only 78% of the time in laboratory testing.
- Consecutive SAM (AASHTO T 395 2024) test results were highly variable compared to consecutive Type B pressure meter (AASHTO T 152 2024) test results obtained from laboratory testing. The interquartile range of percent differences between consecutive SAM (AASHTO T 395 2024) results was 91% compared to 17% for consecutive Type B pressure meter (AASHTO T 152 2024) results.
- The SAM (AASHTO T 395 2024) is significantly more complex and time-consuming to perform compared to using the Type B pressure meter in accordance with AASHTO T 152 (2024). The SAM (AASHTO T 395 2024) requires 26 steps to complete and takes approximately 14 minutes on average. Using the Type B pressure meter in

accordance with AASHTO T 152 (2024) requires only 6 steps to complete and takes approximately 4 minutes on average to complete.

- The SAM meter is not recommended for implementation by ALDOT.

7.2.5. Other Factors Affecting Concrete Mixture's Freeze-Thaw Durability

7.2.5.1. Type of Air-Entraining Admixture

- Some studies found differences in the quality and stability of the air-void systems of concrete mixtures made with synthetic and natural air-entraining admixtures (Freeman 2012; Tanesi and Meininger 2006).
- Despite potential differences between the air-void systems of concrete mixtures produced with synthetic and natural air-entraining admixtures, Felice et al. (2014) suggest that as long as the total air content in the concrete is at least 3.5% or 11% in the cement paste, the concrete will have adequate freeze-thaw resistance regardless of the type of air-entraining admixture used.
- Using literature-derived data, multivariable linear regression analysis provided contradictory results and it is not clear whether concrete mixtures made using synthetic or natural air-entraining admixtures are more freeze-thaw durable.
- Laboratory testing results suggest that there is no difference in the freeze-thaw durability of concrete mixtures made using synthetic and natural air-entraining admixtures.

7.2.5.2. Inclusion of Polycarboxylate-Based High-Range Water-Reducing (PC HRWR) Admixtures

- The literature reviewed suggests that the inclusion of PC HRWR admixture may negatively impact the air-void system and therefore the freeze-thaw durability of concrete mixtures.
- Based on multivariable linear regression analysis of literature-derived data, some concrete mixtures containing PC HRWR admixture may perform adequately while others may not. Because the effect of PC HRWR admixtures is variable, the multivariable linear regression analysis did not find it to be statistically significant at the 99% confidence interval.
- Laboratory testing data suggest that the inclusion of PC HRWR admixture negatively impacts the air-void system and therefore worsens the concrete mixture's freeze-thaw durability. Some concrete mixtures containing PC HRWR admixture had durability factors less than 60 despite them having total air contents greater than 3.5%.
- Overall, between the literature reviewed, the analysis of literature-derived data, and laboratory testing data, there is sufficient evidence to suggest that the inclusion of PC HRWR admixture may cause concrete mixtures to have poor freeze-thaw durability.

7.2.5.3. Water-to-Cementing Materials Ratio (w/cm)

- The literature reviewed suggests that the w/cm does not significantly affect the freeze-thaw durability of properly air-entrained concrete mixtures. For non-air-entrained concrete mixtures with inadequate air-void systems, decreasing the w/cm may moderately improve freeze-thaw durability.

- Multivariable linear regression analysis of literature-derived data yielded conflicting results regarding the influence of w/cm on concrete's freeze-thaw resistance. Results in Section 4.8.1 suggested that decreasing the w/cm slightly improved the freeze-thaw resistance of concrete mixtures while results in Section 4.8.2 found the opposite. The insignificant effect of the w/cm is small compared to that of the total air content and spacing factor variables which suggests that w/cm is much less influential than the air-void system in impacting concrete's freeze-thaw resistance.
- Based on the laboratory testing phase conducted during this project, no relationship was found between the durability factor and w/cm in laboratory testing.

7.2.5.4. Permeability

The influence of permeability on concrete mixtures' freeze-thaw durability was investigated in the literature review. Current literature suggests that like the w/cm, permeability does not significantly influence the freeze-thaw resistance of properly air-entrained concrete mixtures. For non-air-entrained concrete mixtures with inadequate air-void systems, decreasing the permeability may moderately improve freeze-thaw durability by increasing the time it takes for mixtures to become critically saturated.

7.2.5.5. Strength

The influence of concrete strength was investigated in the literature reviewed and in laboratory testing.

- Overall, the literature reveals that like the w/cm and permeability, strength only has a moderate influence on the freeze-thaw durability of non-air-entrained concrete but has no significant influence on the freeze-thaw durability of air-entrained concrete mixtures with adequate air-void systems.
- Based on laboratory testing, no relationship was found between the durability factor and concrete strength.

7.3 Recommendations

Based on the literature reviewed, the analysis of literature-derived data, and the laboratory testing phase conducted during this project, the following items are recommended:

- The minimum total air content in both ALDOT 450 and ALDOT 501 should be increased to 3.5%.
- ALDOT should use a total air content range of 3.5 to 7.0% for all new concrete construction.
- ALDOT should continue to use the Type B pressure meter and not implement the use of the SAM for quality assurance testing.
- In concrete mixtures in which polycarboxylate-based high-range water-reducing (PC HRWR) admixtures are used, the concrete should be protected from cycles of freezing and thawing. This can be done by either preventing concrete structures from becoming critically saturated or by ensuring that the internal temperature of the concrete does not reach 28 °F.

- Potential future research should investigate the properties of PC HRWR admixtures to determine which types of PC HRWR admixtures negatively impact the air-void system of concrete mixtures.
- More concrete mixtures with combinations of synthetic and natural air-entraining admixtures and PC HRWR admixtures should be tested to determine which admixture combinations produce concrete mixtures that are freeze-thaw durable.

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APPENDIX A

DATA ANALYSIS RESULTS NOT INCLUDED IN CHAPTER 4

A.1 Multivariable Linear Regression Analysis Models not included in Section 4.8

Multivariable linear regression analysis models not included in Section 4.8 due to not every variable being statistically significant to the α = 0.01 level are included in this subsection.

Table A-1. Multivariable Linear Regression (MVLR) Analysis Results for Models MVLR 7 through MVLR 10.

Model	**MVLR 7**	**MVLR 8**	**MVLR 9**	**MVLR 10**
Adjusted R^2	0.43	0.43	0.43	0.43
Standard Error	0.75	0.75	0.75	0.75
Significance F	1.84E-48	1.12E-46	2.23E-47	1.14E-47
Variable	***p*-value**			
S_AEA_A	--	9.91E-02	6.53E-02	4.48E-02
PC_HRWR_A	--	2.65E-01	--	--
w/cm	1.08E-03	2.18E-03	4.25E-03	2.25E-03
TAC (%)	1.71E-45	1.64E-43	3.62E-45	8.01E-45
w/cm x TAC (%)	4.82E-02	1.28E-01	6.37E-02	
Variable	***t*-statistic**			
S_AEA_A	--	1.65	1.85	2.01
PC_HRWR_A	--	-1.12	--	--
w/cm	-3.29	-3.09	-2.88	-3.08
TAC (%)	16.20	15.75	16.14	16.06
w/cm x TAC (%)	1.98	1.52	1.86	--
Variable	**β Coefficient**			
S_AEA_A	--	0.19	0.21	0.23
PC_HRWR_A	--	-0.15	--	--
w/cm	-0.13	-0.13	-0.11	-0.12
TAC (%)	0.62	0.64	0.63	0.63
w/cm x TAC (%)	0.07	0.06	0.07	--

Table A-2. Multivariable Linear Regression (MVLR) Analysis Results for Models MVLR 11 through MVLR 15.

Model	MVLR 11	MVLR 12	MVLR 13	MVLR 14	MVLR 15
TAC (%) Threshold	**2.5**	**3**	**3.5**	**4**	**4**
Adjusted R^2	0.45	0.49	0.46	0.43	0.42
Standard Error	0.74	0.71	0.74	0.76	0.76
Significance F	6.25E-50	5.85E-56	8.52E-51	1.23E-46	8.18E-47
Variable	***p*-value**				
<x% TAC	9.39E-05	5.10E-11	1.14E-05	9.28E-01	7.88E-01
S_AEA_A	2.55E-02	3.00E-02	1.85E-02	4.68E-02	--
w/cm	1.38E-02	2.06E-02	3.92E-03	2.33E-03	4.15E-04
TAC (%)	7.36E-22	1.11E-06	2.14E-07	3.08E-15	2.67E-15
Variable	***t*-statistic**				
<x% TAC	-3.95	-6.76	-4.45	0.09	0.27
S_AEA_A	2.24	2.18	2.37	1.99	--
w/cm	-2.47	-2.32	-2.90	-3.06	-3.56
TAC (%)	10.22	4.95	5.28	8.22	8.24
Variable	**β Coefficient**				
<x% TAC	-0.40	-0.86	-0.68	0.02	0.05
S_AEA_A	0.25	0.23	0.26	0.22	--
w/cm	-0.10	-0.09	-0.11	-0.12	-0.14
TAC (%)	0.50	0.30	0.37	0.63	0.64

Table A-3. Multivariable Linear Regression (MVLR) Analysis Results for Models MVLR 16 through MVLR 20.

Model	**MVLR 16**	**MVLR 17**	**MVLR 18**	**MVLR 19**	**MVLR 20**
SF (in.) Threshold	**--**	**0.008**	**0.01**	**0.012**	**0.008**
Adjusted R^2	0.36	0.37	0.38	0.38	0.38
Standard Error	0.80	0.79	0.78	0.79	0.79
Significance F	1.56E-20	1.02E-20	1.76E-21	2.36E-21	1.41E-21
Variable	***p*-value**				
>x in. SF	--	2.83E-02	3.83E-03	5.33E-03	2.79E-02
S_AEA_A	9.70E-01	9.99E-01	9.76E-01	9.47E-01	--
w/cm	1.08E-02	9.48E-03	6.98E-03	6.16E-03	8.67E-03
SF (in.)	4.45E-22	2.48E-12	4.65E-08	9.44E-07	2.09E-12
Variable	***t*-statistic**				
>x in. SF	--	-2.21	-2.93	-2.82	-2.21
S_AEA_A	-0.04	0.00	-0.03	-0.07	--
w/cm	2.57	2.62	2.73	2.77	2.65
SF (in.)	-10.89	-7.46	-5.68	-5.06	-7.48
Variable	**β Coefficient**				
>x in. SF	--	-0.36	-0.47	-0.47	-0.36
S_AEA_A	-0.01	0.00	0.00	-0.01	--
w/cm	0.14	0.15	0.15	0.15	0.15
SF (in.)	-0.61	-0.51	-0.44	-0.43	-0.51

A.2 Logistic Regression Analysis Models not included in Section 4.9

Logistic regression analysis models not included in Section 4.9 due to not every variable being statistically significant to the α = 0.01 level are included in this subsection.

Table A-4. Logistic Regression (LR) Analysis Results for Models LR 15 through LR 18.

Logistic Regression Analysis	**LR 15**	**LR 16**	**LR 17**	**LR 18**
≥x DF Threshold	**60**	**60**	**60**	**60**
<x% TAC Threshold	**2.5**	**3.0**	**3.5**	**4.0**
Area Under ROC Curve	0.863	0.864	0.863	0.865
AIC	364.5	362.8	364.1	359.8
Maximum VIF	1.76	2.85	3.48	4.03
Variable	***p*-values**			
<x% TAC	0.82	0.19	0.51	0.03
S_AEA_A	0.20	0.22	0.19	0.21
TAC (%)	1.76E-09	1.30E-06	2.06E-07	3.65E-13
w/cm	0.74	0.70	0.76	0.60
Variable	**β Coefficients**			
<x% TAC	0.02	-0.17	-0.10	0.38
S_AEA_A	0.09	0.09	0.09	0.09
TAC (%)	1.50	1.22	1.34	1.83
w/cm	0.03	0.03	0.02	0.04

Table A-5. Logistic Regression (LR) Analysis Results for Models LR 19 through LR 22.

Logistic Regression Analysis	**LR 19**	**LR 20**	**LR 21**	**LR 22**
>=x DF Threshold	**60**	**60**	**60**	**60**
<x% TAC Threshold	**2.5**	**3.0**	**3.5**	**4.0**
Area Under ROC Curve	0.860	0.861	0.861	0.862
AIC	364.2	362.3	363.8	359.4
Maximum VIF	1.76	2.85	3.47	4.03
Variable	***p*-values**			
<x% TAC	0.79	0.17	0.52	0.02
TAC (%)	2.33E-09	1.77E-06	2.44E-07	3.94E-13
w/cm	0.99	0.93	0.98	0.82
Variable	**β Coefficients**			
<x% TAC	0.03	-0.18	-0.10	0.38
TAC (%)	1.49	1.18	1.32	1.80
w/cm	0.00	0.01	0.00	0.02

Table A-6. Logistic Regression (LR) Analysis Results for Models LR 23 through LR 26.

Logistic Regression Analysis	**LR 23**	**LR 24**	**LR 25**	**LR 26**
>=x DF Threshold	**60**	**60**	**60**	**60**
<x% TAC Threshold	**2.5**	**3.0**	**3.5**	**4.0**
Area Under ROC Curve	0.757	0.798	0.797	0.755
AIC	448.5	393.3	396.4	432.9
Maximum VIF	1.05	1.05	1.03	1.01
Variable	***p*-values**			
<x% TAC	0.00E+00	0.00E+00	0.00E+00	1.44E-13
w/cm	0.39	0.66	0.22	0.04
Variable	**β Coefficients**			
<x% TAC	-0.59	-0.83	-0.89	-0.77
w/cm	-0.06	-0.03	-0.09	-0.14

APPENDIX B

CHEMICAL ADMIXTURE DOSAGES FOR EACH CONCRETE MIXTURE

Chemical Admixture Dosages for Each Concrete Mixture

Table A-7 shows the air-entraining admixture (AEA) and water-reducing admixture (WRA) dosages for each concrete mixture produced and tested in this study's laboratory testing program.

Table A-7. Air-Entraining (AE) and Water-Reducing (WR) Admixture Dosages for Each Concrete Mixtures with w/cm=0.35 and 0.40 Tested in this Study.

Mixture ID	AEA Dosage (fl. oz./100 cwt)	WRA Dosage (fl. oz./100 cwt)
0.35: N+PC1 1	0.25	6
0.35: N+PC1 2	0.20	4.5
0.35: S+PC2 1	0.10	7
0.35: S+PC2 2	0.07	7
0.35: S+PC2 3	0.52	7
0.35: S+PC2 4	0.075	7
0.35: S+PC2 5	0.13	7
0.35: PC1 1	--	6
0.40: S+WR 1	0.3	7
0.40: S+WR 2	0.3	7
0.40: S+WR 3	0.42	11

Table A-8. Air-Entraining (AE) and Water-Reducing (WR) Admixture Dosages for Each Concrete Mixtures with w/cm=0.45 and 0.50 Tested in this Study.

Mixture ID	AEA Dosage (fl. oz./100 cwt)	WRA Dosage (fl. oz./100 cwt)
0.45: N+WR 1	0.25	4
0.45: N+WR 2	0.35	3.5
0.45: N+WR 3	0.7	3
0.45: N+WR 4	0.9	11
0.45: N+WR 5	0.25	4
0.45: N+WR 6	0.55	3.5
0.45: N+WR 7	0.4	4.5
0.45: N+WR 8	0.25	6.5
0.45: N+WR 9	0.45	7.5
0.45: N+WR 10	0.55	13
0.45: S+WR 1	0.4	5
0.45: S+WR 2	0.8	7
0.45: S+WR 3	0.6	6
0.45: S+WR 4	0.5	6
0.45: S+WR 5	0.45	5
0.45: S+WR 6	0.47	5.5
0.45: S+WR 7	0.46	7.5
0.45: WR 1	--	4.5
0.50: S+WR 1	0.5	10
0.50: S+WR 2	0.6	6
0.50: S+WR 3	0.4	4.5
0.50: S+WR 5	0.6	5
0.50: S+WR 6	0.65	5

APPENDIX C

FRESH CONCRETE TESTING RESULTS NOT INCLUDED IN CHAPTER 5

C.1 Fresh Concrete Testing Results not included in Chapter 5

Table A-8 shows all abbreviations used in Appendix C and their definitions. Table A-9 (a) and (b) show all fresh concrete testing results not included in Chapter 5. These include the unit weight, gravimeter total air content, first and second total air contents determined using the Type B pressure meter, first and second total air contents determined using the SAM meter, and the first and second SAM numbers determined using the SAM meter. The abbreviations ERR and N/D in Table A-9 stand for “Equipment Error” and “Not Determined,” respectively. Equipment errors are reported when the SAM meter gives an “error” reading instead of reporting a SAM number. In cases where results are labeled as N/D, this was caused by there being an insufficient amount of concrete remaining to perform a test or the research team forgetting to perform a test.

Table A-9. Abbreviations used in Appendix C and their Definitions.

Abbreviation	Definition
ρ	Unit Weight
Grav. TAC	Gravimetric Total Air Content
TAC 1	1st Total Air Content Result from Type B Pressure Meter
TAC 2	2nd Total Air Content Result from Type B Pressure Meter
SAM TAC 1	1st Total Air Content Result from SAM Meter
SAM TAC 2	2nd Total Air Content Result from SAM Meter
SAM #1	1st SAM Number Result
SAM #2	2nd SAM Number Result

Table A-10. Fresh Concrete Testing Results for Mixtures with w/cm=0.35 and 0.40 not Included in Chapter 5.

Result	Slump	Temperature
Units	(in.)	(°F)
Mixture ID		
0.35: N+PC1 1	7.50	70
0.35: N+PC1 2	5.00	--
0.35: S+PC2 1	3.75	75
0.35: S+PC2 2	4.75	76
0.35: S+PC2 3	3.50	76
0.35: S+PC2 4	4.50	72
0.35: S+PC2 5	4.00	72
0.35: PC1 1	3.50	71
0.40: S+WR 1	2.50	62
0.40: S+WR 2	3.50	69
0.40: S+WR 3	3.50	68

Table A-10. Fresh Concrete Testing Results for Mixtures with w/cm=0.45 and 0.50 not Included in Chapter 5.

Result	**Slump**	**Temperature**
Units	**(in.)**	**(°F)**
Mixture ID		
0.45: N+WR 1	5.00	--
0.45: N+WR 2	4.25	--
0.45: N+WR 3	8.00	74
0.45: N+WR 4	2.50	81
0.45: N+WR 5	2.75	79
0.45: N+WR 6	3.50	76
0.45: N+WR 7	4.25	75
0.45: N+WR 8	3.25	76
0.45: N+WR 9	3.75	76
0.45: N+WR 10	1.75	76
0.45: S+WR 1	3.50	68
0.45: S+WR 2	4.75	78
0.45: S+WR 3	4.00	79
0.45: S+WR 4	4.50	76
0.45: S+WR 5	4.25	79
0.45: S+WR 6	3.50	78
0.45: S+WR 7	4.50	67
0.45: WR 1	3.00	71
0.50: S+WR 1	3.50	79
0.50: S+WR 2	6.00	68
0.50: S+WR 3	3.75	77
0.50: S+WR 3	4.25	66
0.50: S+WR 5	3.00	68
0.50: S+WR 6	3.50	78

APPENDIX D

HARDENED CONCRETE TESTING RESULTS NOT INCLUDED IN CHAPTER 5

D.1 Relative Dynamic Modulus of Elasticity versus Number of Freezing and Thawing Cycles Completed Curves

This section includes figures that show the relative dynamic modulus of elasticity versus number of freezing and thawing cycles completed curves for each concrete mixture tested in this study as is recommended in AASHTO T 161 (2022). Also shown is the average relative dynamic modulus of elasticity versus number of freezing and thawing cycles completed.

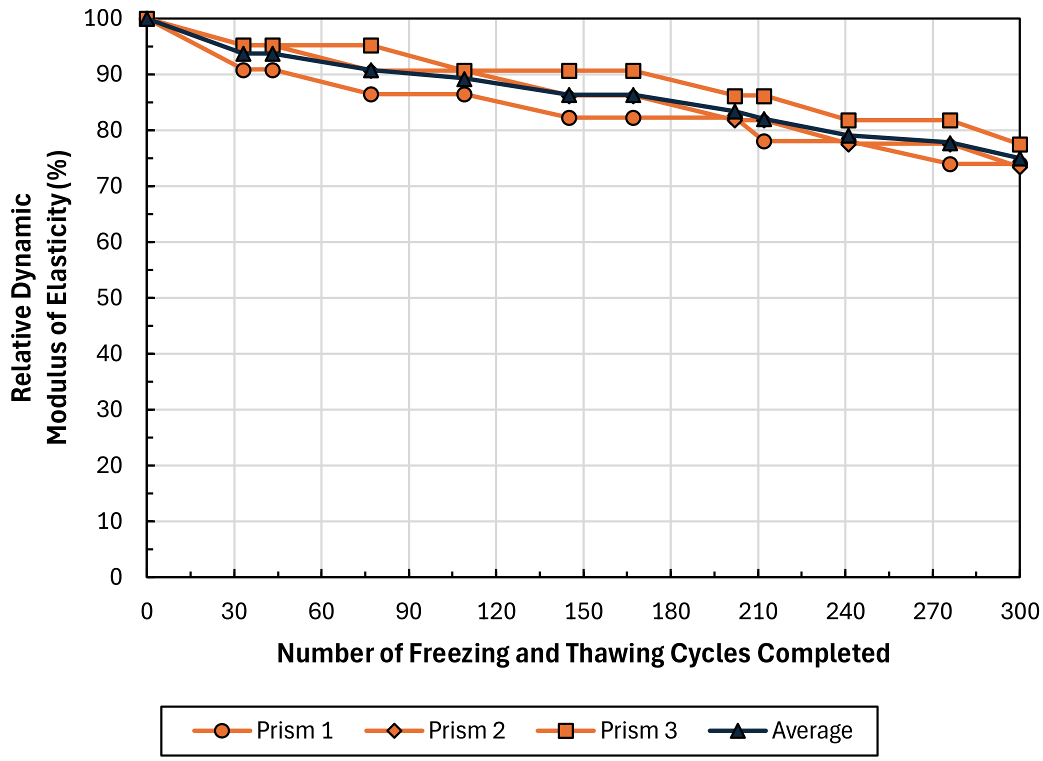

Figure A-1. Relative Dynamic Modulus of Elasticity versus Number of Freezing and Thawing Cycles Completed. Mixture ID: 0.35: N+PC1 1.

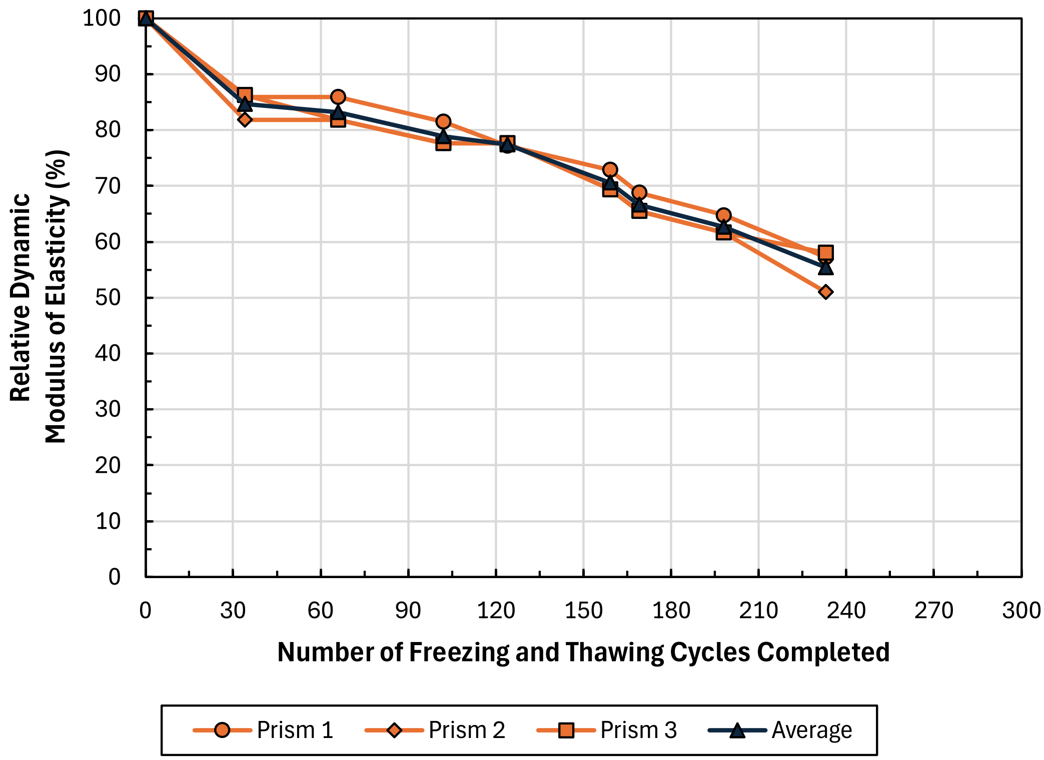

Figure A-2. Relative Dynamic Modulus of Elasticity versus Number of Freezing and Thawing Cycles Completed. Mixture ID: 0.35: N+PC1 2.

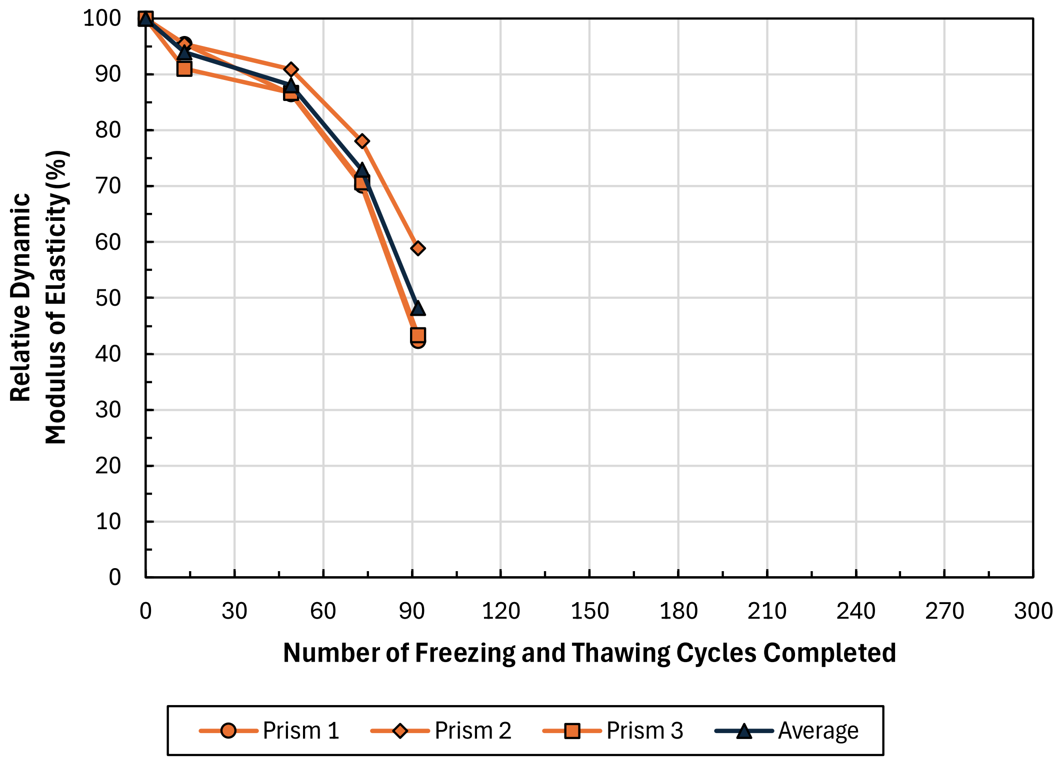

Figure A-3. Relative Dynamic Modulus of Elasticity versus Number of Freezing and Thawing Cycles Completed. Mixture ID: 0.35: S+PC2 1.

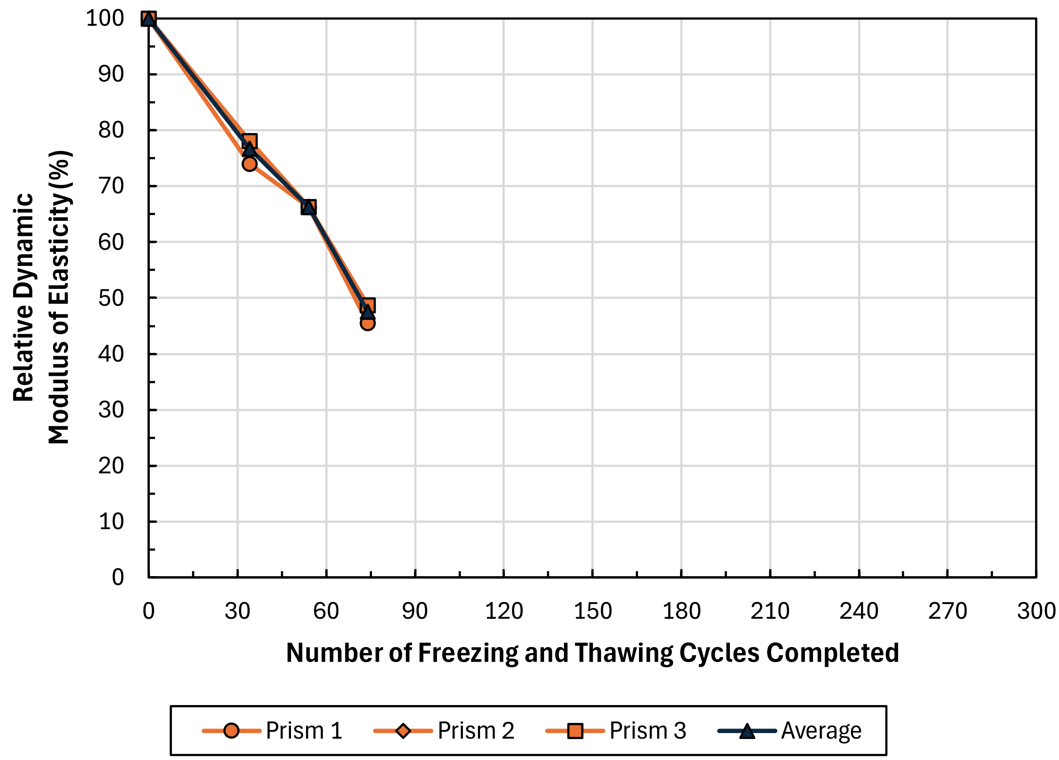

Figure A-4. Relative Dynamic Modulus of Elasticity versus Number of Freezing and Thawing Cycles Completed. Mixture ID: 0.35: S+PC2 2.

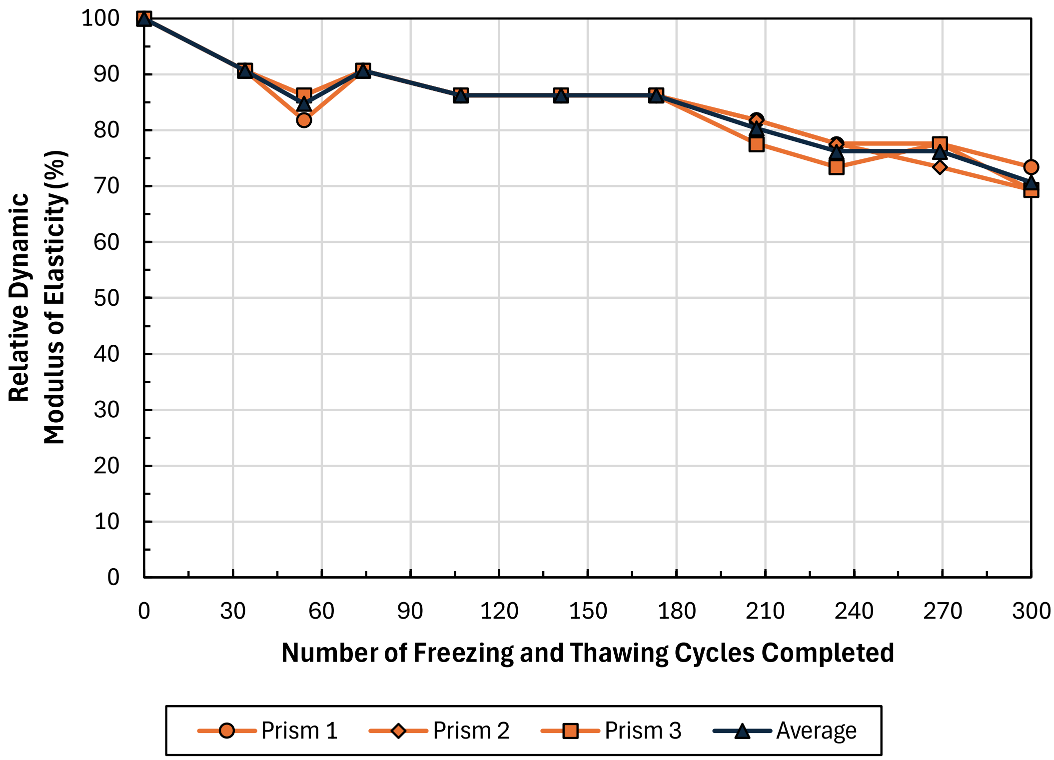

Figure A-5. Relative Dynamic Modulus of Elasticity versus Number of Freezing and Thawing Cycles Completed. Mixture ID: 0.35: S+PC2 3.

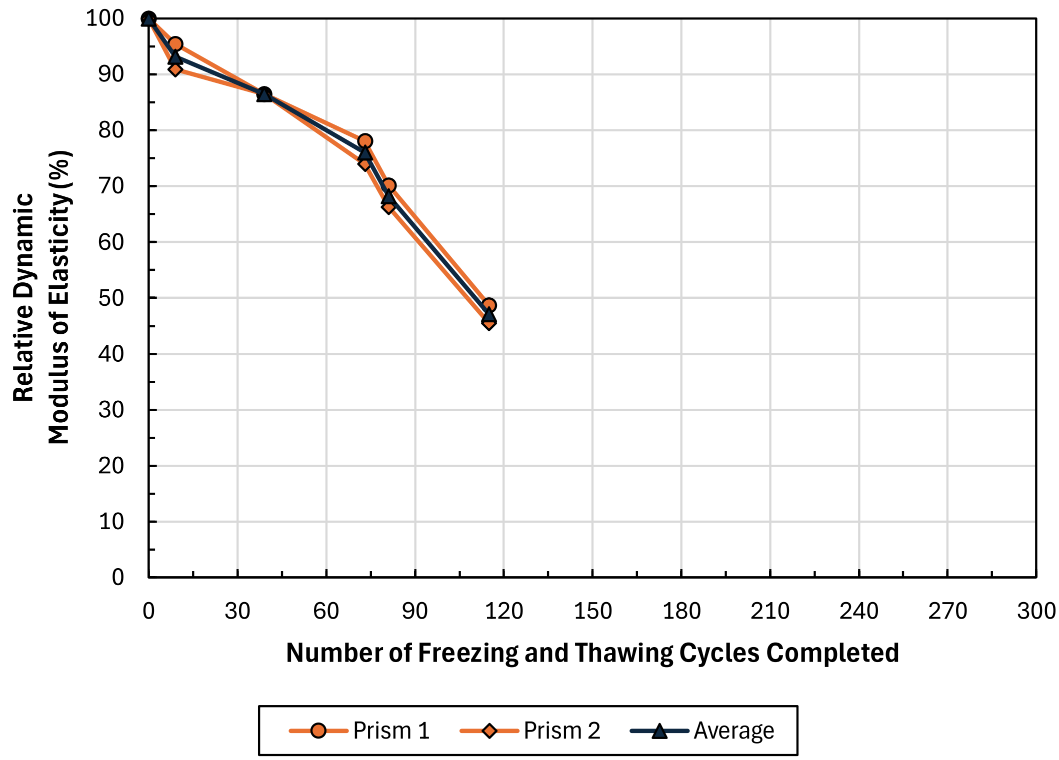

Figure A-6. Relative Dynamic Modulus of Elasticity versus Number of Freezing and Thawing Cycles Completed. Mixture ID: 0.35: S+PC2 4.

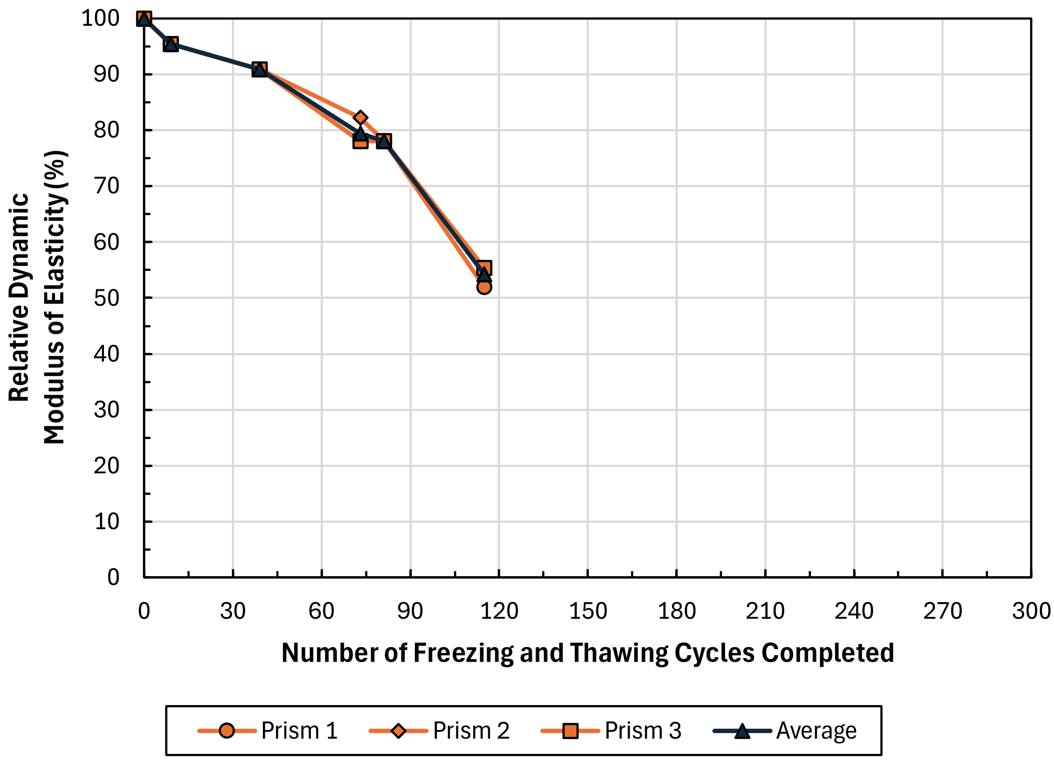

Figure A-7. Relative Dynamic Modulus of Elasticity versus Number of Freezing and Thawing Cycles Completed. Mixture ID: 0.35: S+PC2 5.

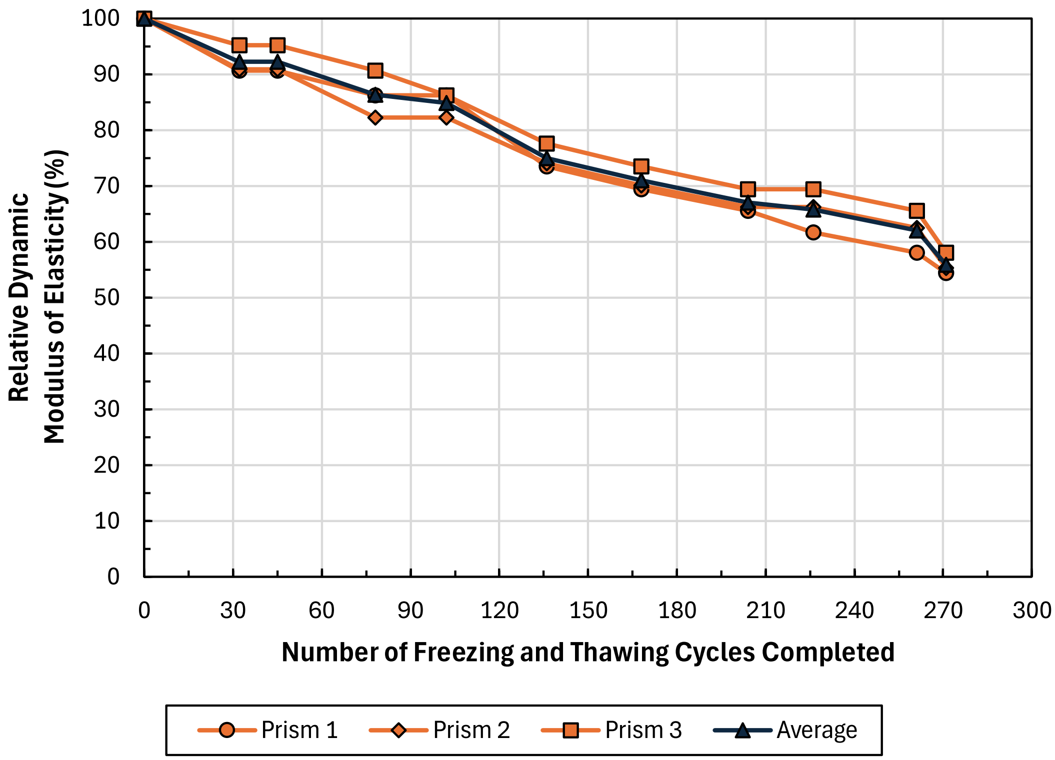

Figure A-8. Relative Dynamic Modulus of Elasticity versus Number of Freezing and Thawing Cycles Completed. Mixture ID: 0.35: PC1 1.

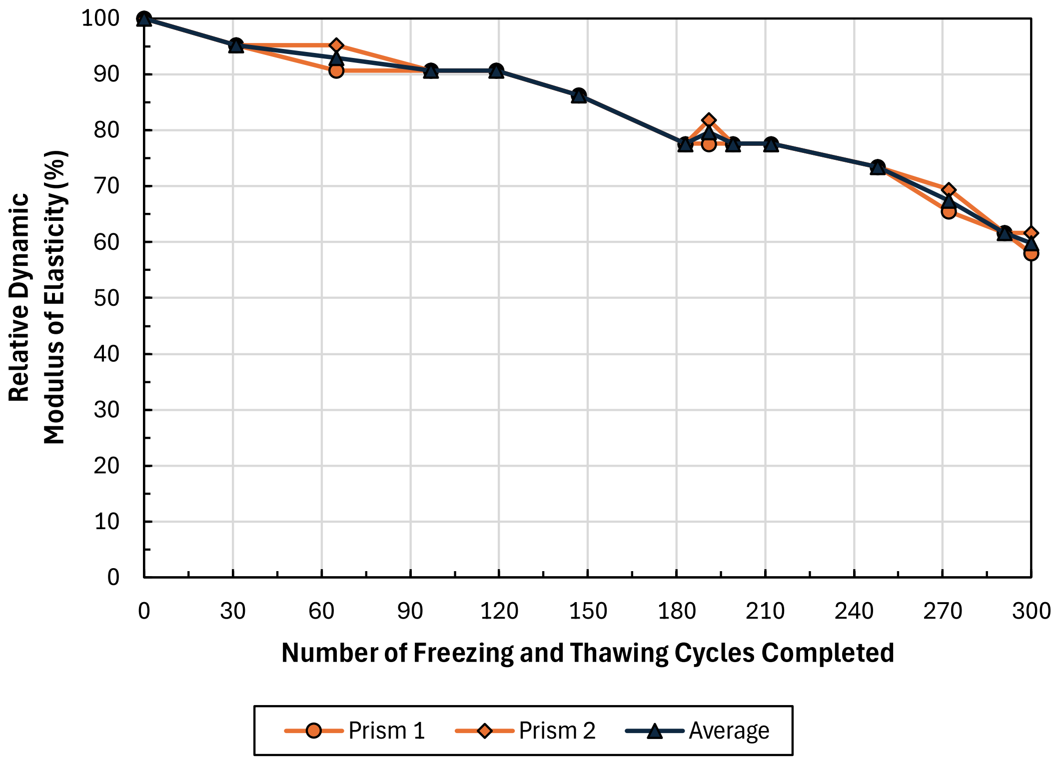

Figure A-9. Relative Dynamic Modulus of Elasticity versus Number of Freezing and Thawing Cycles Completed. Mixture ID: 0.40: S+WR 1.

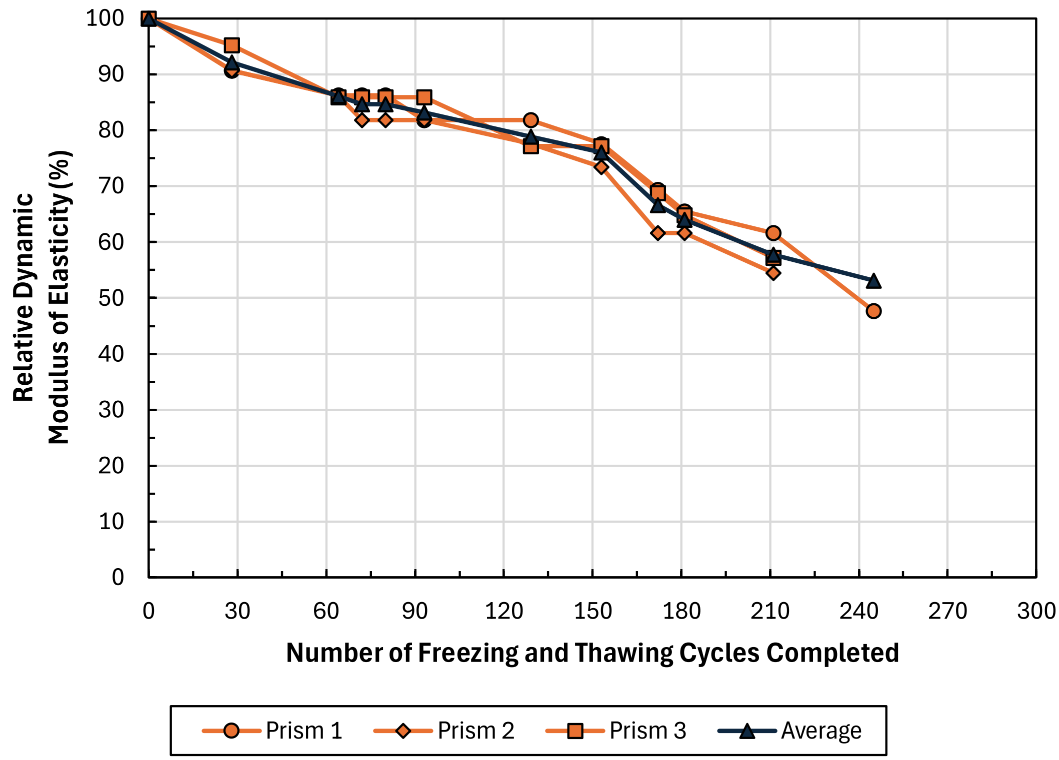

Figure A-10. Relative Dynamic Modulus of Elasticity versus Number of Freezing and Thawing Cycles Completed. Mixture ID: 0.40: S+WR 2.

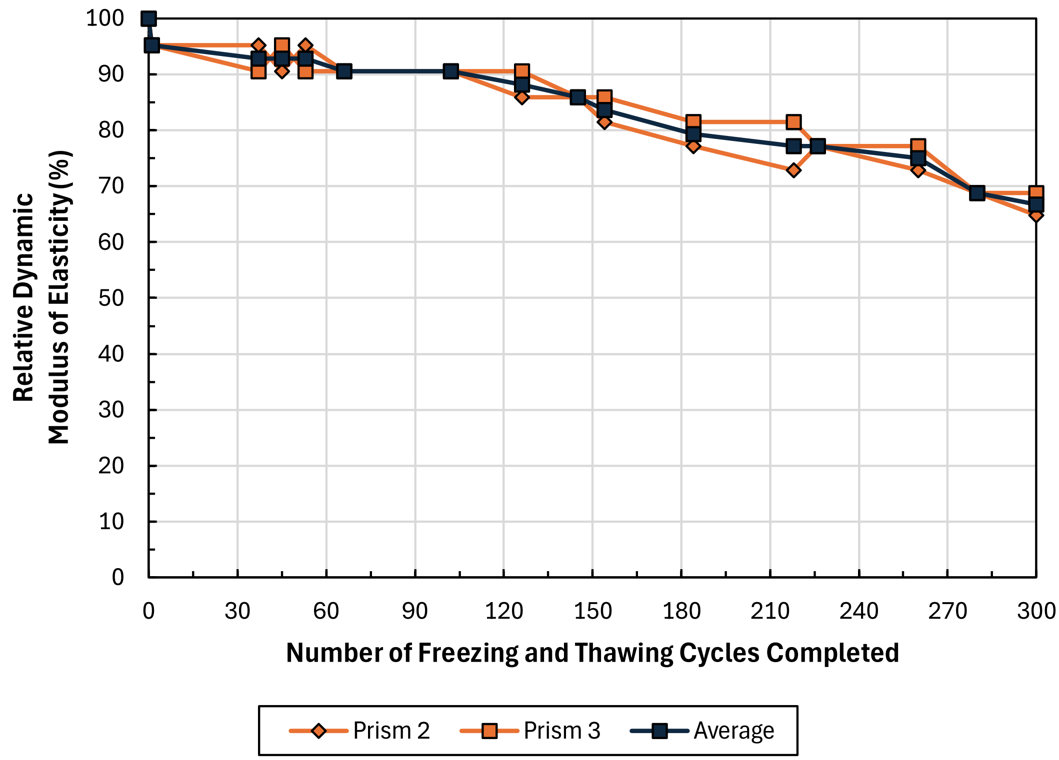

Figure A-11. Relative Dynamic Modulus of Elasticity versus Number of Freezing and Thawing Cycles Completed. Mixture ID: 0.40: S+WR 3.

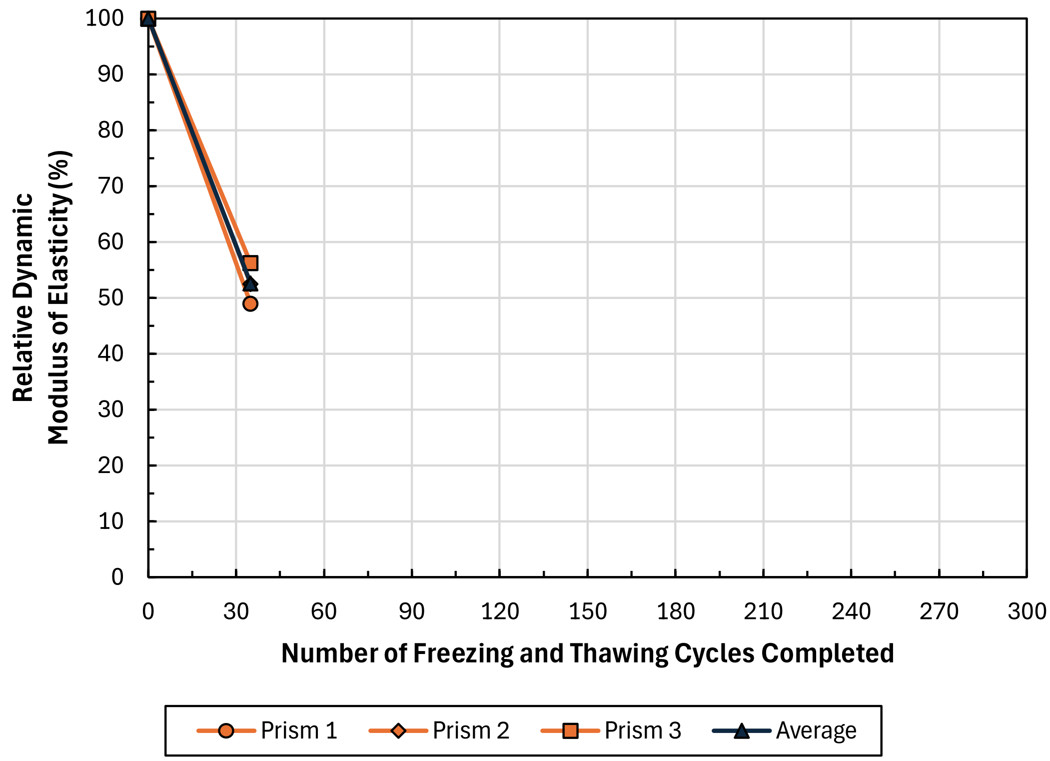

Figure A-12. Relative Dynamic Modulus of Elasticity versus Number of Freezing and Thawing Cycles Completed. Mixture ID: 0.45: N+WR 1.

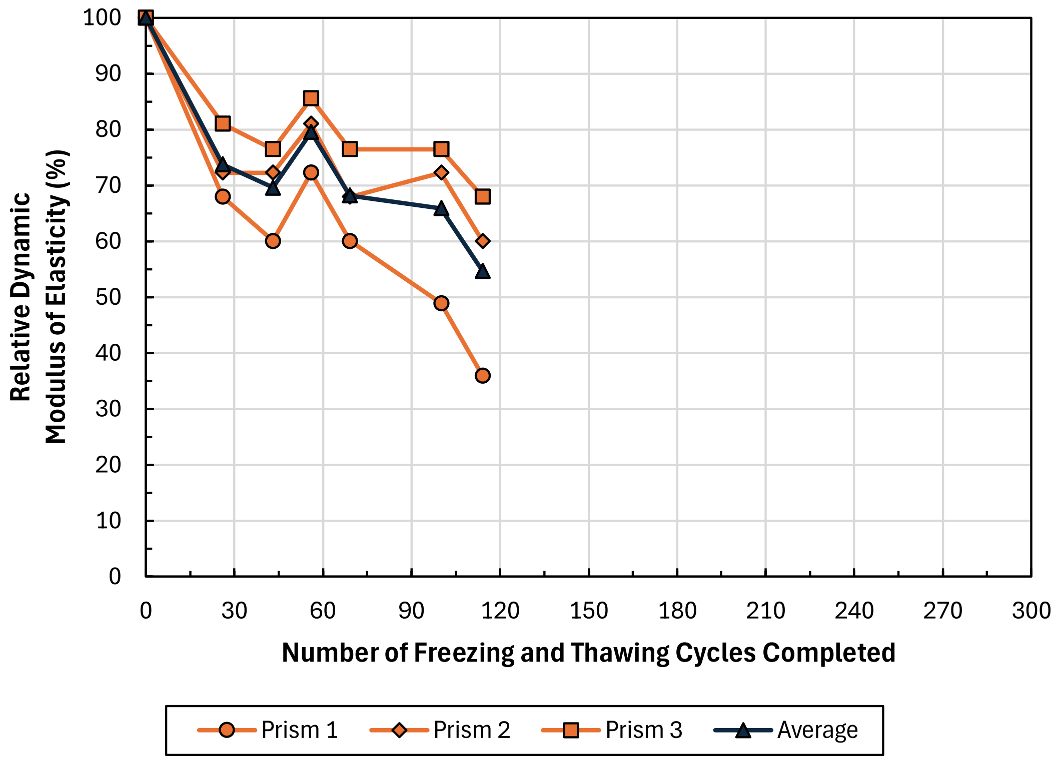

Figure A-13. Relative Dynamic Modulus of Elasticity versus Number of Freezing and Thawing Cycles Completed. Mixture ID: 0.45: N+WR 2.

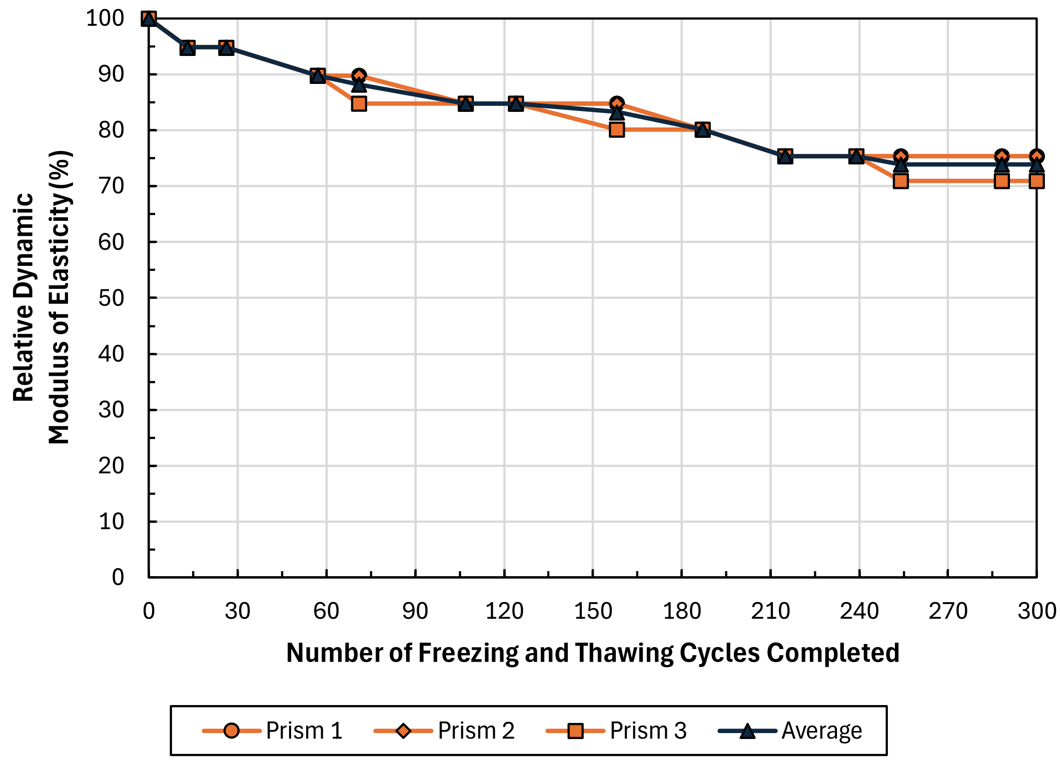

Figure A-14. Relative Dynamic Modulus of Elasticity versus Number of Freezing and Thawing Cycles Completed. Mixture ID: 0.45: N+WR 3.

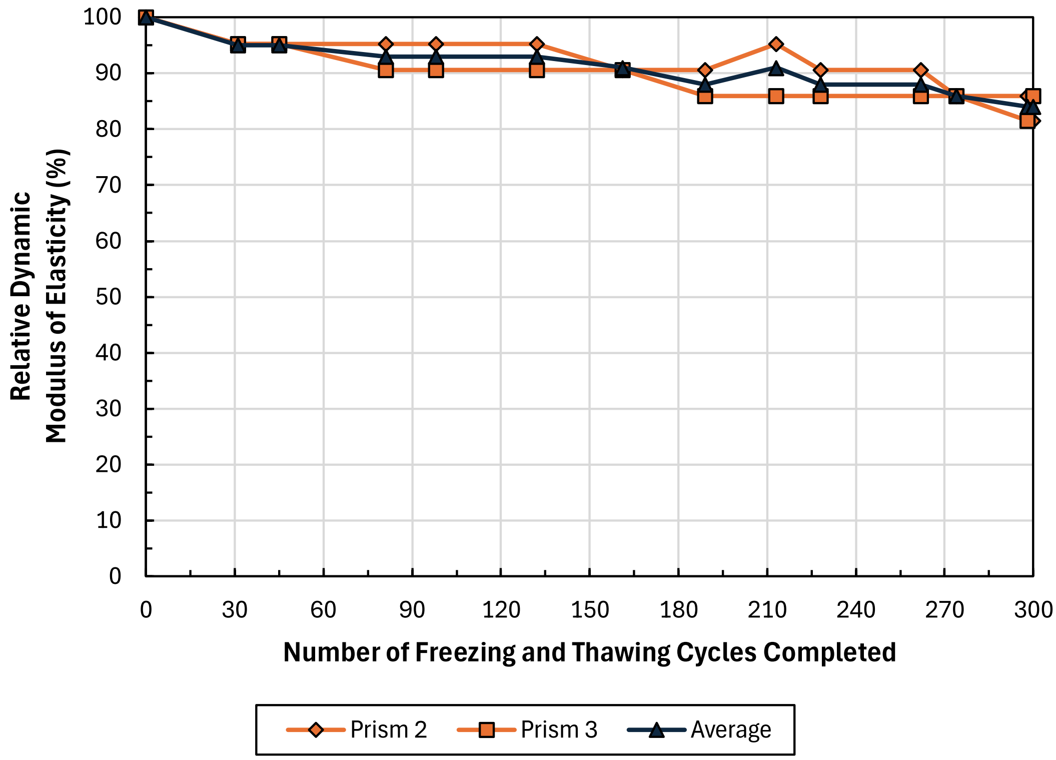

Figure A-15. Relative Dynamic Modulus of Elasticity versus Number of Freezing and Thawing Cycles Completed. Mixture ID: 0.45: N+WR 4.

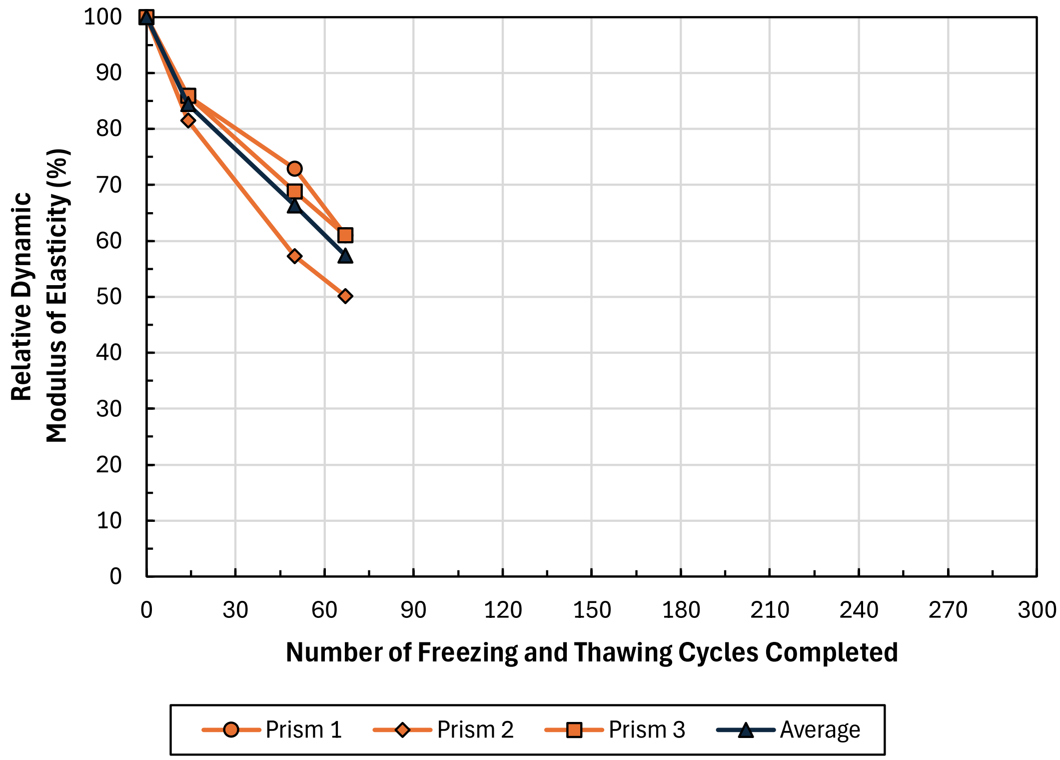

Figure A-16. Relative Dynamic Modulus of Elasticity versus Number of Freezing and Thawing Cycles Completed. Mixture ID: 0.45: N+WR 5.

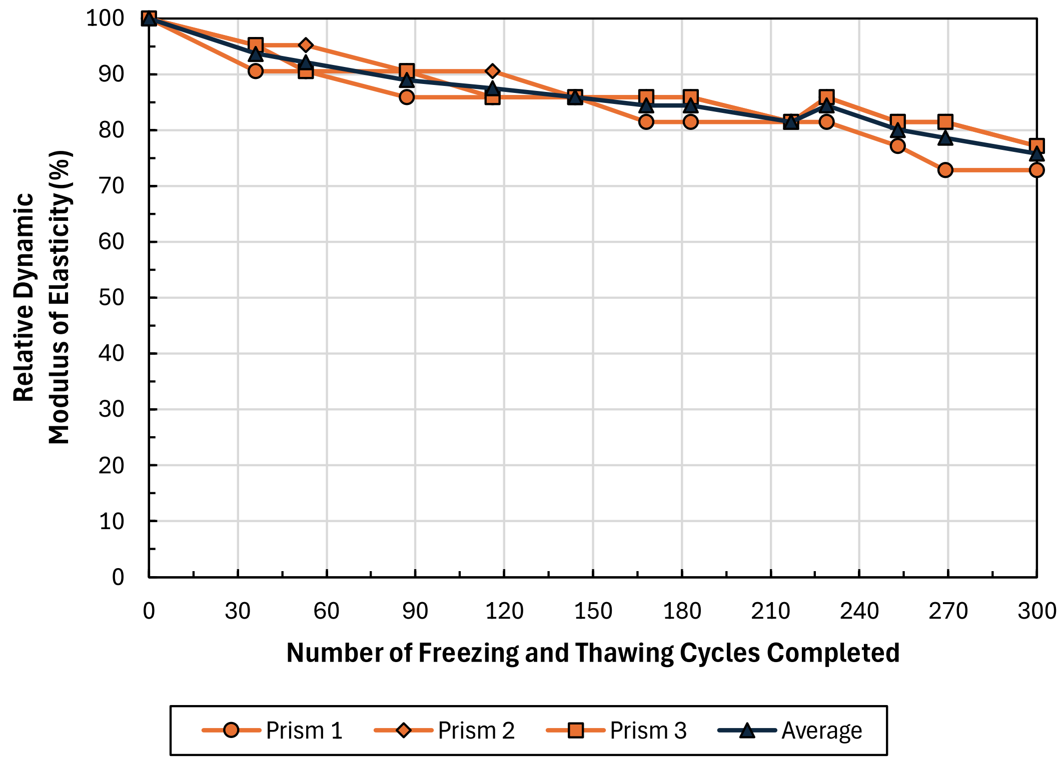

Figure A-17. Relative Dynamic Modulus of Elasticity versus Number of Freezing and Thawing Cycles Completed. Mixture ID: 0.45: N+WR 6.

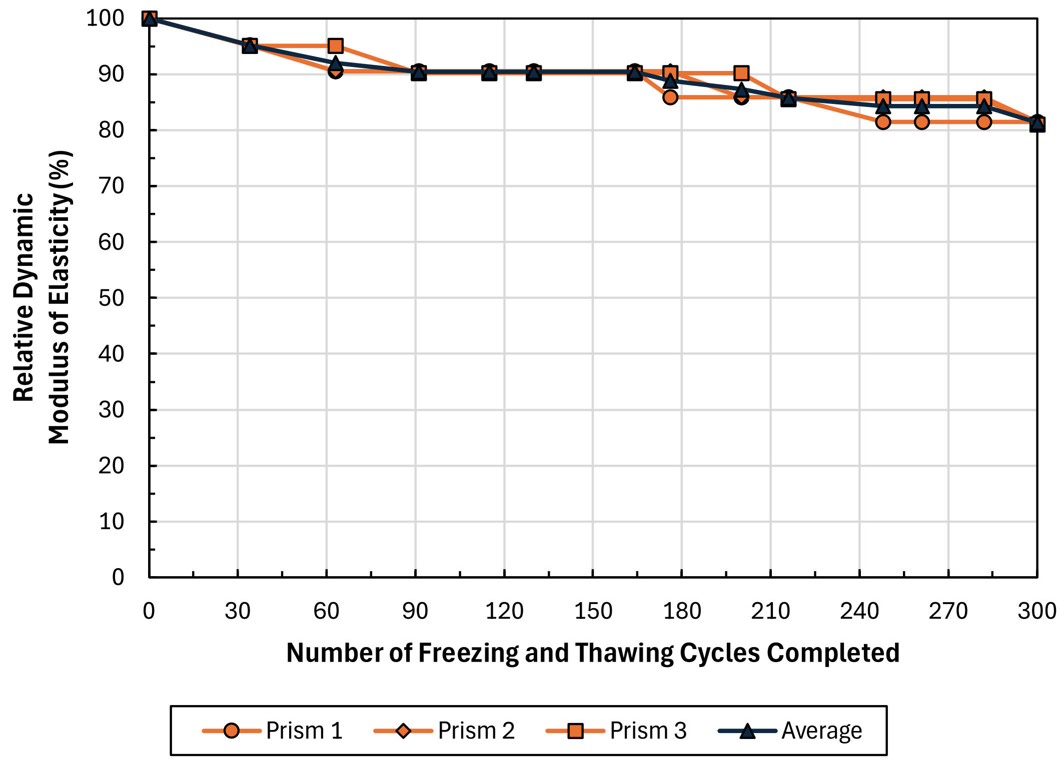

Figure A-18. Relative Dynamic Modulus of Elasticity versus Number of Freezing and Thawing Cycles Completed. Mixture ID: 0.45: N+WR 7.

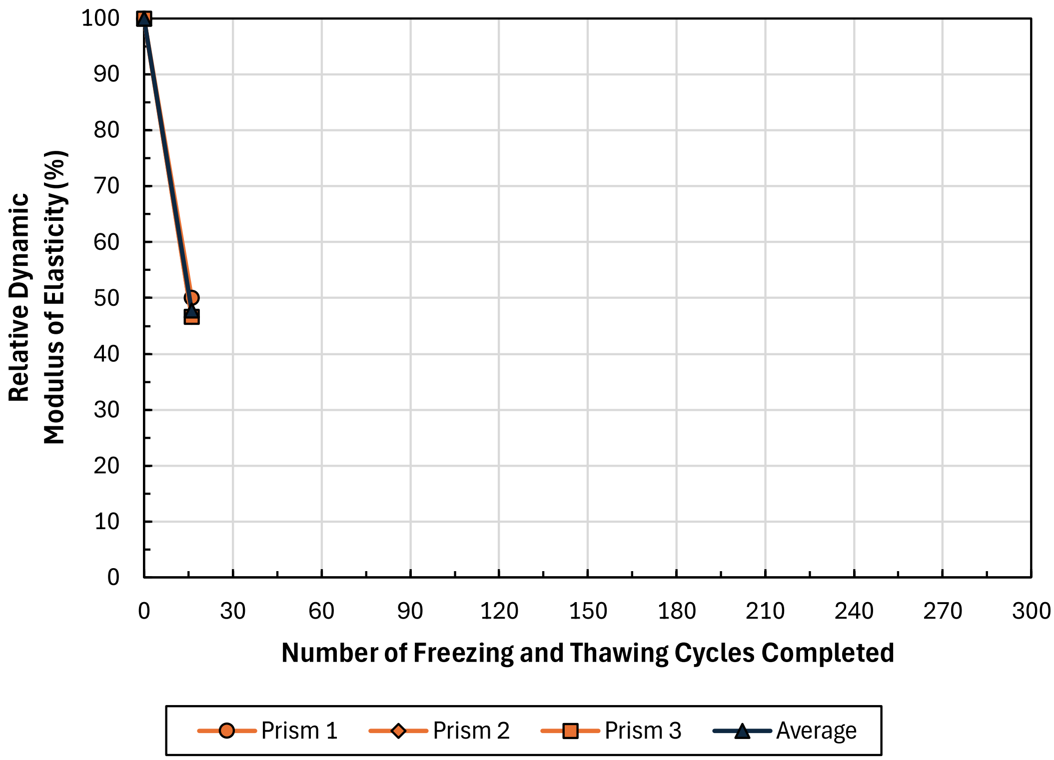

Figure A-19. Relative Dynamic Modulus of Elasticity versus Number of Freezing and Thawing Cycles Completed. Mixture ID: 0.45: N+WR 8.

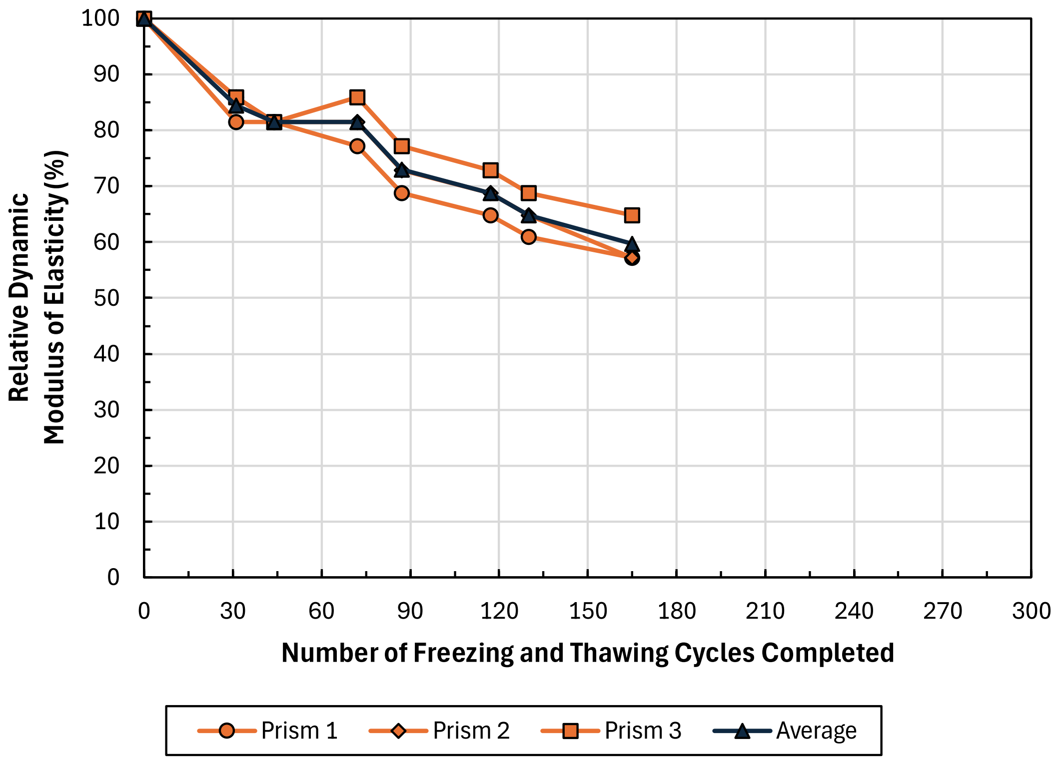

Figure A-20. Relative Dynamic Modulus of Elasticity versus Number of Freezing and Thawing Cycles Completed. Mixture ID: 0.45: N+WR 9.

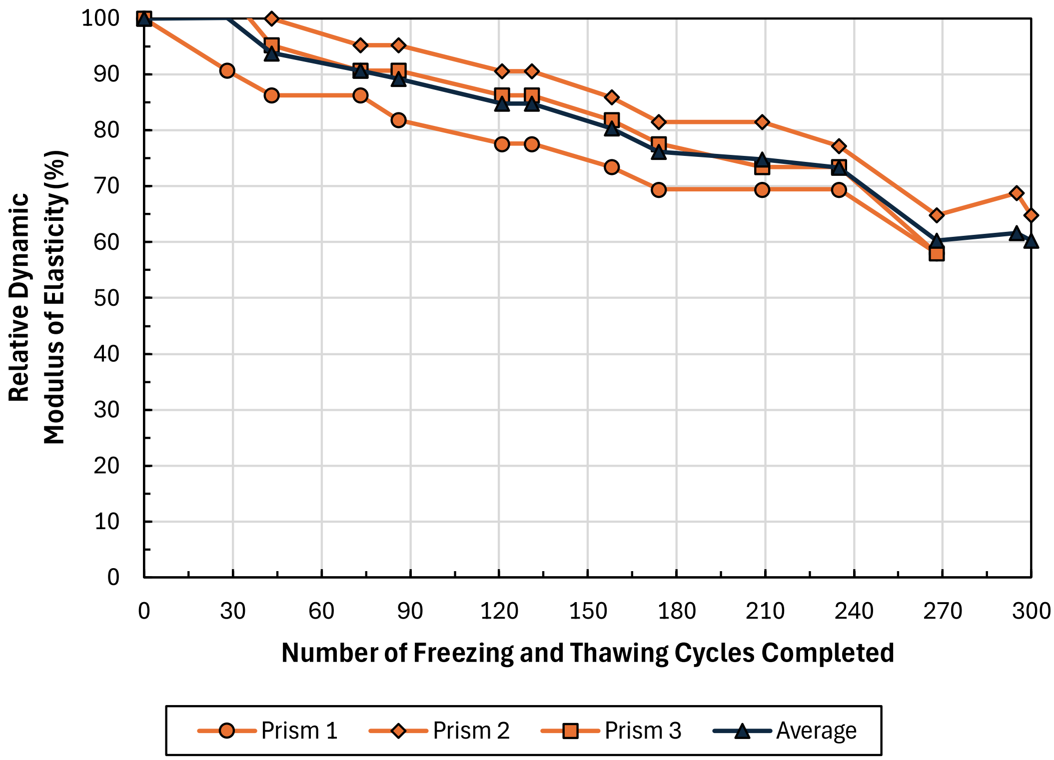

Figure A-21. Relative Dynamic Modulus of Elasticity versus Number of Freezing and Thawing Cycles Completed. Mixture ID: 0.45: N+WR 10.

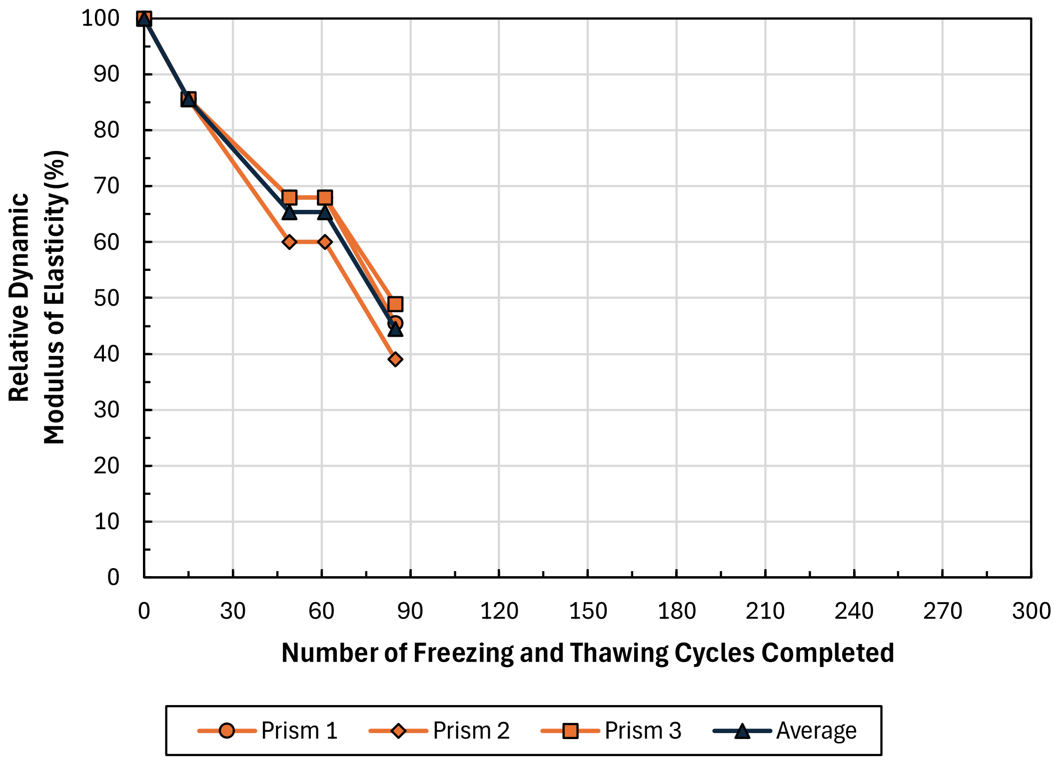

Figure A-22. Relative Dynamic Modulus of Elasticity versus Number of Freezing and Thawing Cycles Completed. Mixture ID: 0.45: S+WR 1.

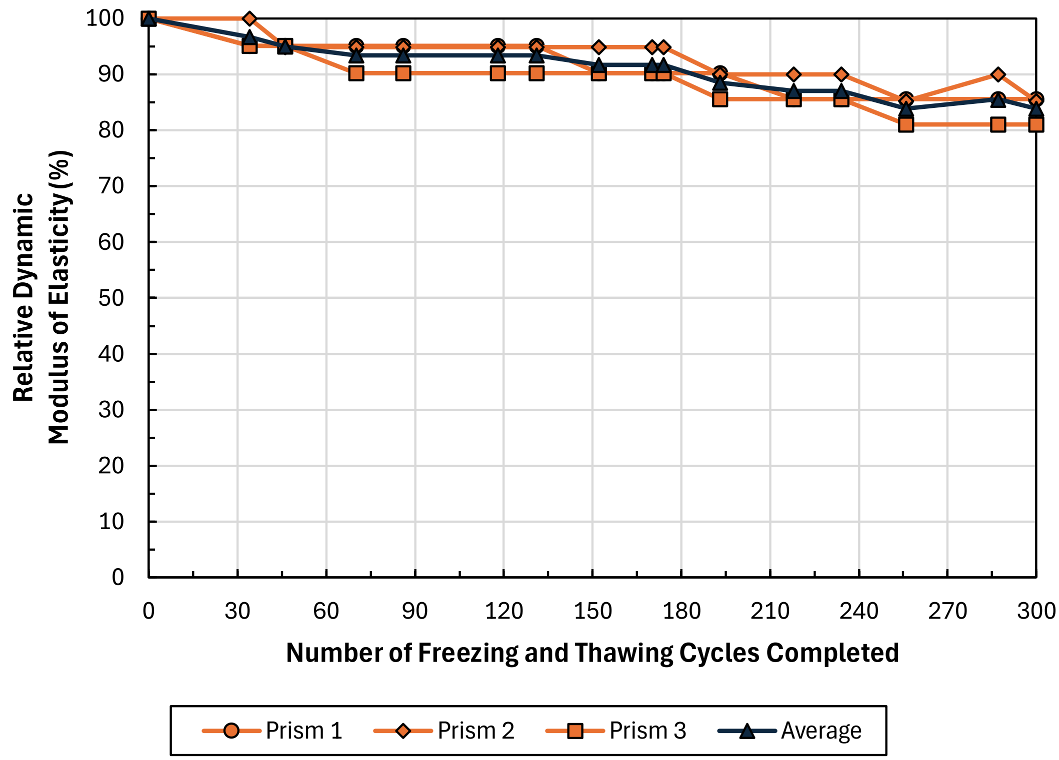

Figure A-23. Relative Dynamic Modulus of Elasticity versus Number of Freezing and Thawing Cycles Completed. Mixture ID: 0.45: S+WR 2.

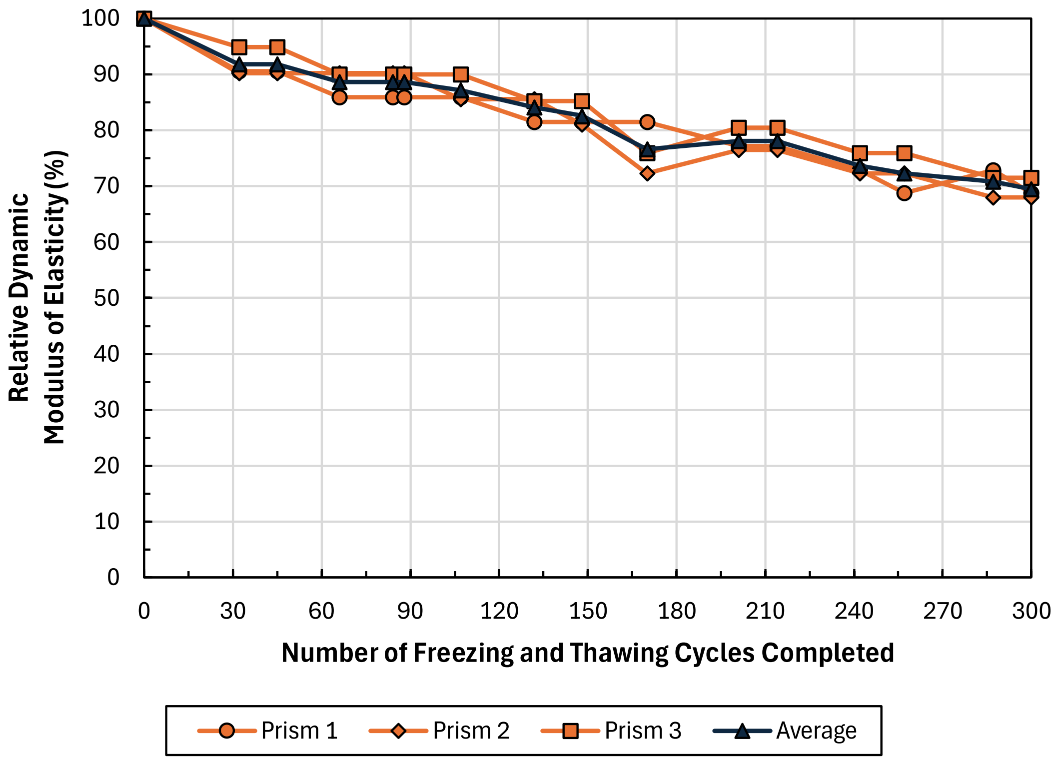

Figure A-24. Relative Dynamic Modulus of Elasticity versus Number of Freezing and Thawing Cycles Completed. Mixture ID: 0.45: S+WR 3.

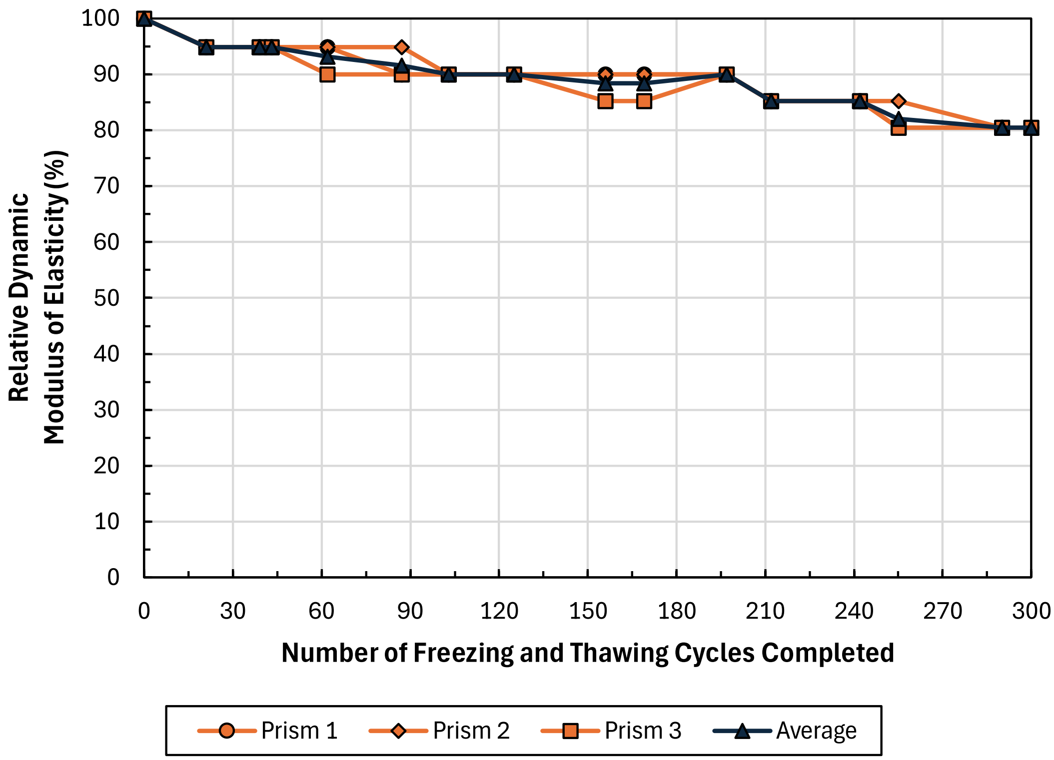

Figure A-25. Relative Dynamic Modulus of Elasticity versus Number of Freezing and Thawing Cycles Completed. Mixture ID: 0.45: S+WR 4.

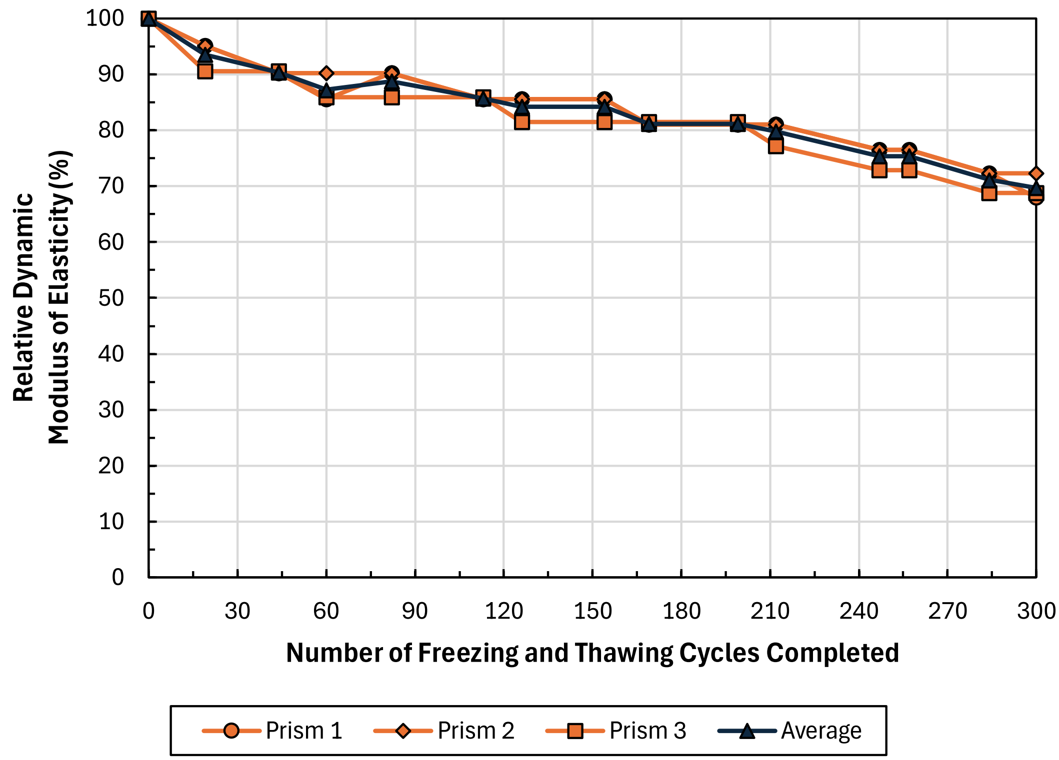

Figure A-26. Relative Dynamic Modulus of Elasticity versus Number of Freezing and Thawing Cycles Completed. Mixture ID: 0.45: S+WR 5.

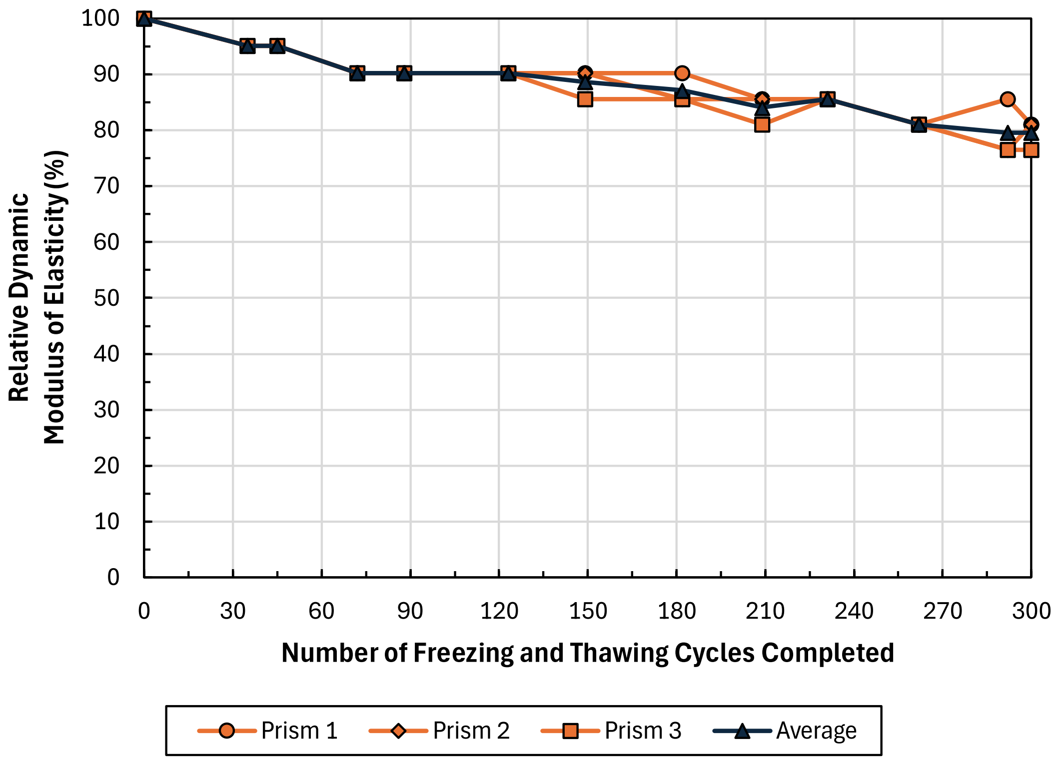

Figure A-27. Relative Dynamic Modulus of Elasticity versus Number of Freezing and Thawing Cycles Completed. Mixture ID: 0.45: S+WR 6.

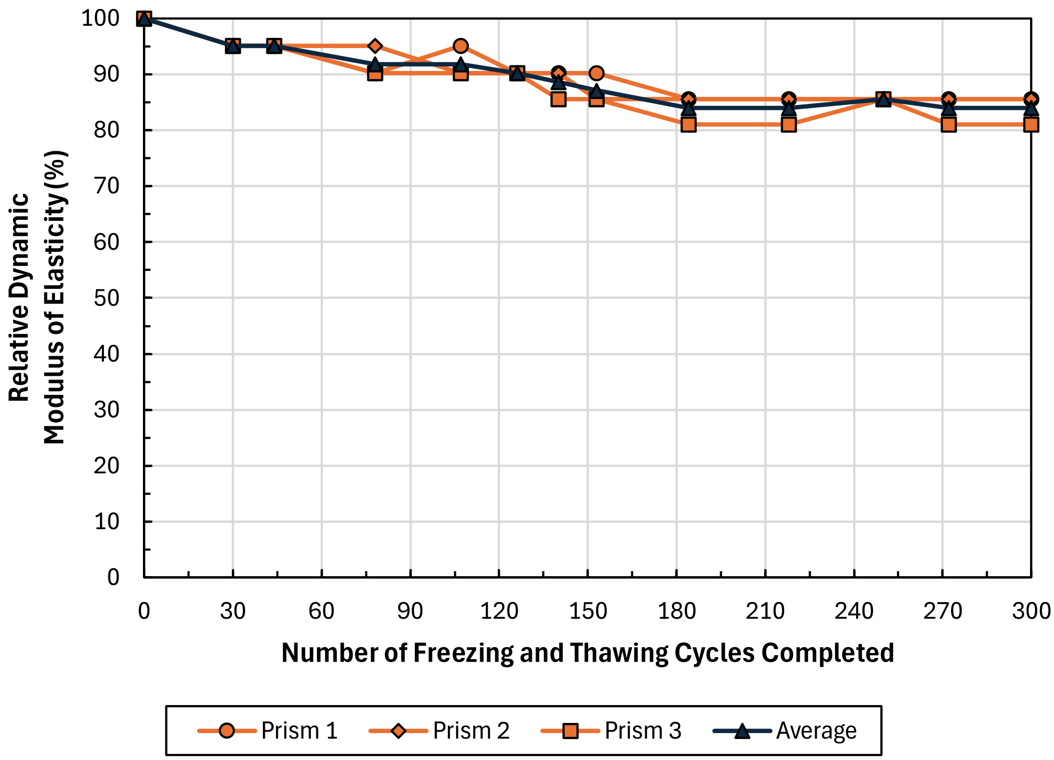

Figure A-28. Relative Dynamic Modulus of Elasticity versus Number of Freezing and Thawing Cycles Completed. Mixture ID: 0.45: S+WR 7.

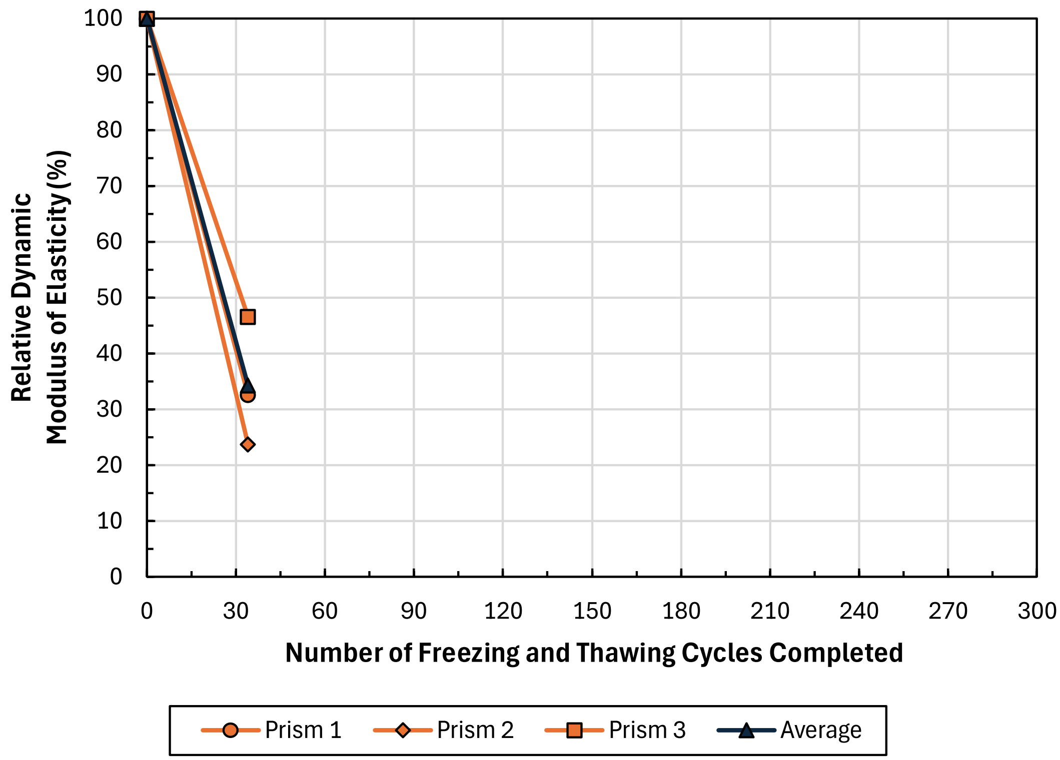

Figure A-29. Relative Dynamic Modulus of Elasticity versus Number of Freezing and Thawing Cycles Completed. Mixture ID: 0.45: WR 1.

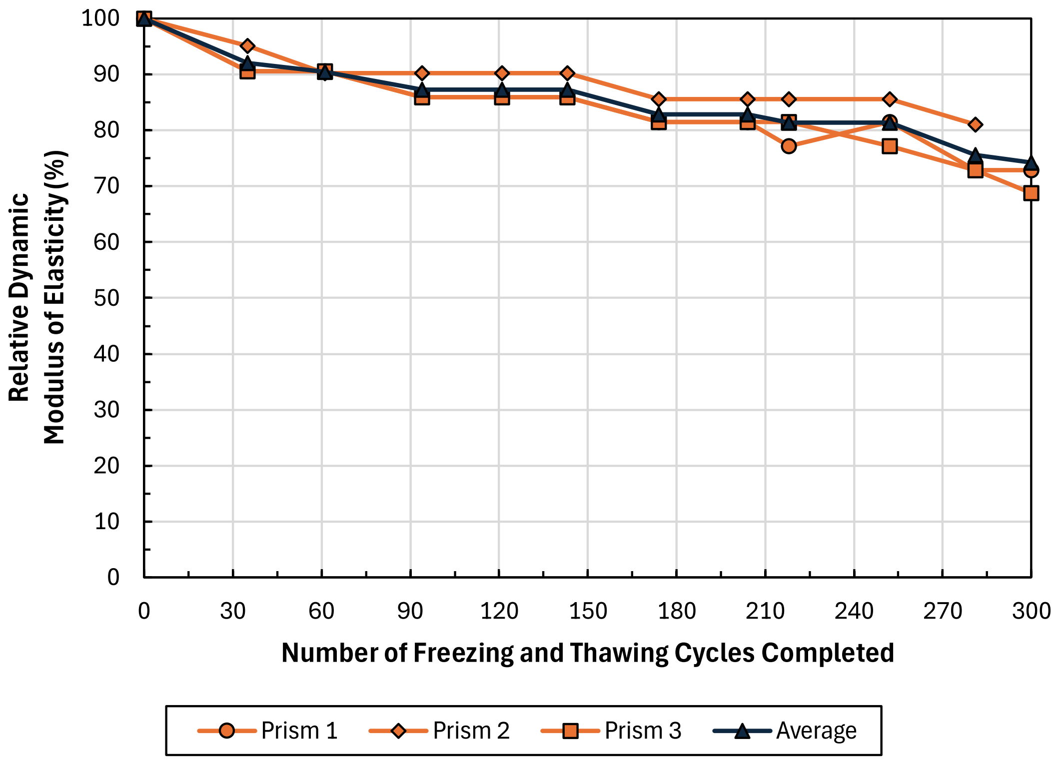

Figure A-30. Relative Dynamic Modulus of Elasticity versus Number of Freezing and Thawing Cycles Completed. Mixture ID: 0.50: S+WR 1.

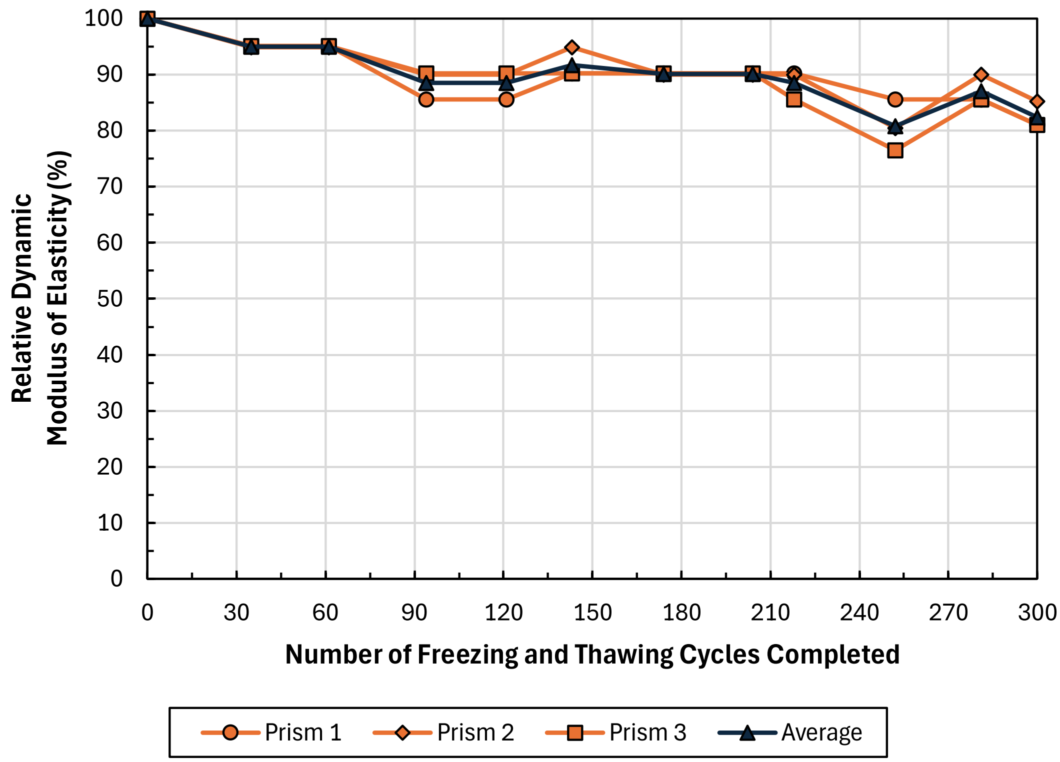

Figure A-31. Relative Dynamic Modulus of Elasticity versus Number of Freezing and Thawing Cycles Completed. 0.50: S+WR 2.

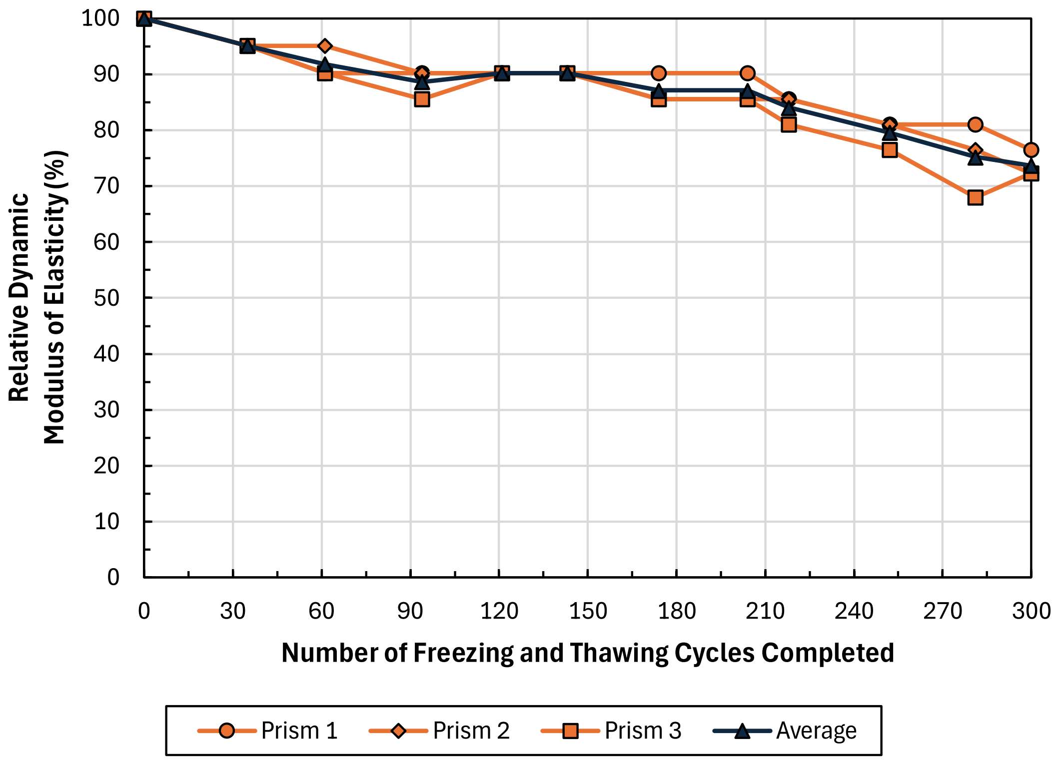

Figure A-32. Relative Dynamic Modulus of Elasticity versus Number of Freezing and Thawing Cycles Completed. 0.50: S+WR 3.

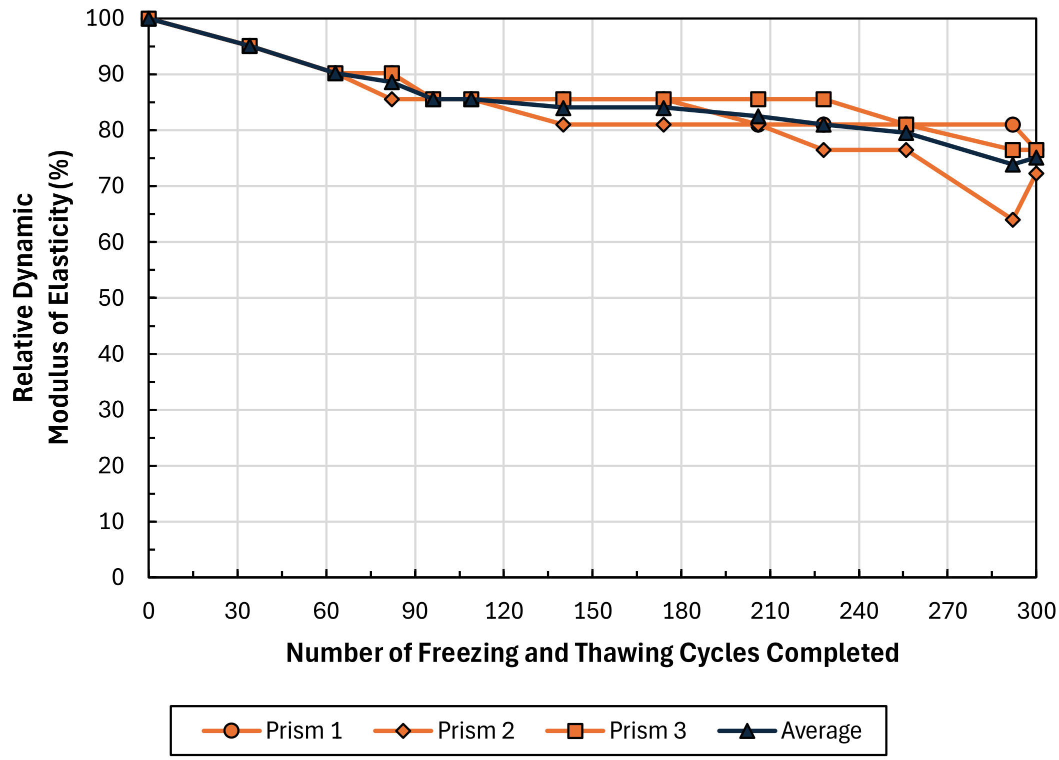

Figure A-33. Relative Dynamic Modulus of Elasticity versus Number of Freezing and Thawing Cycles Completed. 0.50: S+WR 5.

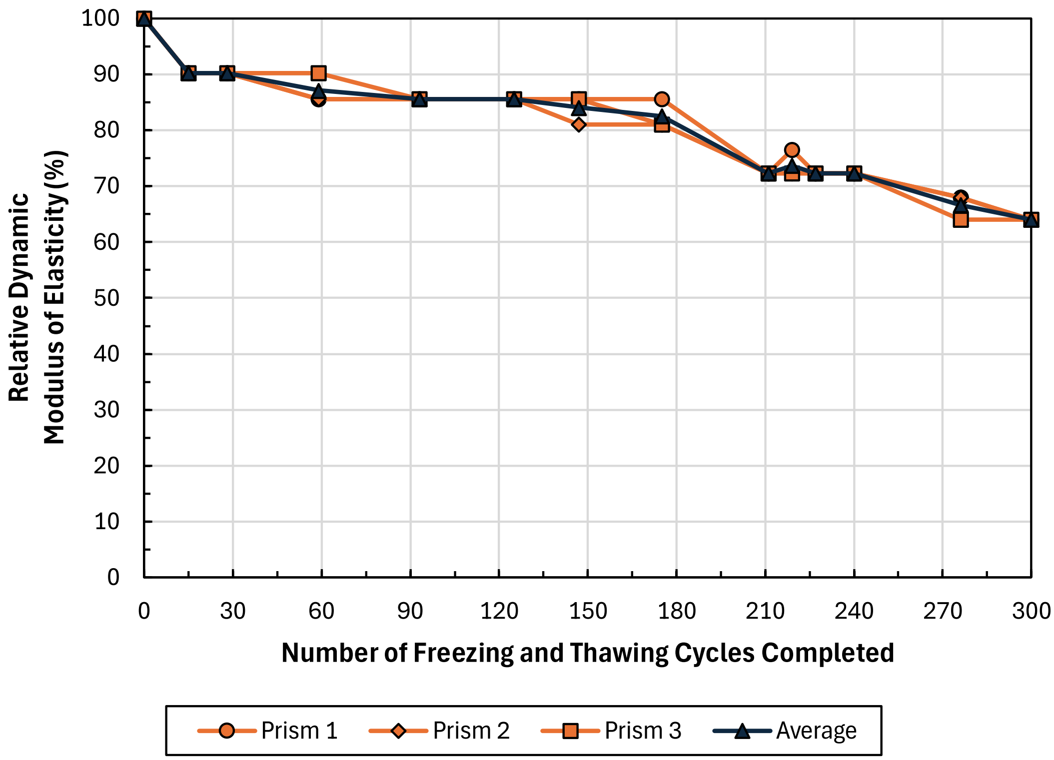

Figure A-34. Relative Dynamic Modulus of Elasticity versus Number of Freezing and Thawing Cycles Completed. 0.50: S+WR 6.