Enhancing Freeze-thaw Resistance of Tennessee Concrete Mixes Through Improved Air Void Testing

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16. Abstract

The quality of the air void system in concrete is critical for the freeze-thaw durability and service life of concrete structures. In Tennessee, the current Tennessee Department of Transportation (TDOT) specification only specifies the air content for fresh concrete mixes. Currently, the most widely used methods to evaluate the freeze-thaw durability and the air void system of concrete include ASTM C666 test, ASTM C457 test, and Air Void Analyzer (AVA) test. However, these test methods are unsuitable for fresh concrete mixes in the field for QC/QA purposes. This study investigates the applicability of Super Air Meter (SAM) to TDOT concrete mixes and the suitability of SAM number as a QC/QA tool for freeze-thaw resistance and determines the acceptance criterion for the SAM number if it can be adopted for QC/QA purposes. The results show that for TDOT concrete mixes, only the fresh air content requirement (e.g., 4%~8% for Class A, 4.5%~7.5% for Class D) does not necessarily guarantee high quality of air void system and enough freeze-thaw resistance. SAM number shows a decreasing trend with the increase of air content of fresh concrete. There is a good correlation between SAM number and freeze-thaw durability factor/spacing factor for TDOT concrete mixes. Therefore, using air content and SAM number as a QC/QA tool for TDOT concrete mixes is feasible. From a conservative perspective, 0.2 can be used as the threshold of SAM number to ensure TDOT concrete mixes have satisfactory freeze-thaw resistance. In addition, it is also feasible to use 0.3 as the upper limit of SAM number for TDOT concrete mixes.

17. Key Words
CONCRETE, FREEZE-THAW, AIR CONTENT, SAM NUMBER, SPACING FACTOR, DURABILITY FACTOR

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Executive Summary

Freeze-thaw damage is the widest deterioration type of concrete structures in cold climate regions. The air-void system in concrete plays a critical role in the resistance of concrete to freezing and thawing cycles by providing additional space to reduce internal pressure caused by frozen water. The air-void concrete system has been characterized by parameters including air content, spacing factor, specific surface.

Currently, the most commonly used methods to evaluate the freeze-thaw durability and air-void system of concrete are ASTM C666/AASHTO T161 freeze-thaw test and ASTM C457 air void parameter test. However, both methods are only used for hardened concrete rather than fresh concrete, seriously lagging behind the construction schedule of concrete. The Air Void Analyzer (AVA) developed by Dansk Beton Teknik can be used to measure the air void parameters of fresh concrete as per AASHTO TP75. But the AVA test device is very sensitive to field conditions, which is not suitable as a quality control/quality assurance (QC/QA) tool. The Super Air Meter (SAM) is a recently developed test device for fresh concrete, which is easily performed on the job site providing results in real-time. Moreover, the SAM number has been found to correlate well to the spacing factor and freeze-thaw durability of concrete.

The main aim of this study was to investigate the applicability of the SAM to Tennessee Department of Transportation (TDOT) concrete mixes and the suitability of the SAM number as a QC/QA tool for freeze-thaw resistance and to determine the acceptance criterion for the SAM number if it can be adopted for QC/QA purpose. To achieve this goal, a synthesis of literature review on the latest advances in the SAM test method and a state Department of Transportation survey on their acceptance criteria of the SAM number for adequate freeze-thaw resistance of concrete were conducted. Then, various concrete mixes in TDOT specifications across Tennessee on the job sites and in the laboratory were tested for their SAM numbers, as well as other air void parameters (e.g., total air content, the spacing factor, and specific surface), and the freeze-thaw durability factor from ASTM C666/AASHTO T161. After that, a comprehensive statistical analysis of the test results was performed to acquire the correlations between the SAM number, freeze-thaw durability factor, and other air-void parameters. Also, the threshold value of the SAM number was determined. Finally, based on the results and findings from this study, recommendations were made to TDOT specifications regarding the application of the SAM and acceptance criteria of the SAM number for TDOT concrete mixes.

Key Findings

- For TDOT concrete mixes, the fresh air content requirement (e.g., 4%~8% for Class A, 4.5%~7.5% for Class D) does not necessarily guarantee high quality of air void system and enough freeze-thaw resistance.
- For TDOT concrete mixes in different regions, the measured SAM number varies widely, indicating there is no good consistency of the SAM number in various locations. The variation of the SAM number actually reflected the difference in the air void system of fresh concrete mixes.
- For TDOT concrete mixes, the SAM number shows a decreasing trend with the increase of air content of fresh concrete.

- For TDOT concrete mixes, there is a good correlation between the SAM number and freeze-thaw durability factor: a SAM number of 0.2 shows a correlation to a durability factor of 80% with 81% agreement; a SAM number of 0.3 shows a correlation to a durability factor of 80% with 85% agreement.
- For TDOT concrete mixes, there is a good correlation between the SAM number and spacing factor: a SAM number of 0.2 shows a correlation to a spacing factor of 0.2 mm with 83% agreement; a SAM number of 0.3 shows a correlation to a spacing factor of 0.3 mm with 89% agreement.

Key Recommendations

- The SAM is applicable to TDOT concrete mixes to evaluate the air void system and freeze-thaw resistance, and the SAM number can be adopted as a QC/QA tool. Not only should the air content for fresh concrete meet TDOT specification (e.g., 4%~8% for Class A, 4.5%~7.5% for Class D), but also an appropriate SAM number is recommended. The following acceptance criteria of a SAM number for TDOT concrete mixes can be adopted:
    - From a conservative perspective, a SAM number below 0.2 can be considered as good enough to ensure concrete has sufficient freeze-thaw durability factor (e.g., higher than 80%);
    - A SAM number between 0.2 and 0.3 can be considered as acceptable to ensure concrete has a freeze-thaw durability factor meeting the failure limit (e.g., higher than 60%); and
    - A SAM number above 0.3 can be considered as rejectable. To remedy such fresh concrete mixes, the most straightforward method is to increase the air content (e.g., adding more air entraining admixture), then the SAM number will decrease to a proper value for acceptance.

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Chapter 1 Introduction

1.1 Research Problem

Weather-induced freezing and thawing is one of the major causes of concrete deterioration in cold climates and must be taken into consideration in concrete structural design [1-2]. Such damage consists primarily of macro- or micro-cracking and surface scaling, which significantly accelerates the ingress of aggressive external agents such as chlorides and sulfates into concrete and consequently results in corrosion [3-4].

Researchers have been studying the intrinsic mechanism governing the freeze-thaw damage for decades and consistently found the generation of internal stress involved in the process, which is the result of a) hydraulic pressure due to ice formation, with a 9% expansion in volume; b) osmotic pressure generated in the pore system by the movement of liquid water towards pores containing ice to restore thermodynamic equilibrium; and c) the pressure induced by the growth of crystals in pores and their interaction with pore walls [5-7].

The air-void system in concrete plays a critical role in the resistance of concrete to freezing and thawing cycles by providing additional space to reduce internal pressure caused by frozen water. The air-void system of concrete has been characterized by parameters including air content, spacing factor, specific surface [1, 8-9]. Therefore, many laboratory test methods have been developed to determine these parameters of concrete mixes. The most widely used is still the pressure air test ASTM C231 [10], first published in 1949, which quantifies the total air volume of fresh concrete mixes. However, the total air content cannot reflect the size and distribution of air voids in concrete, which have shown to be more effective in characterizing the freeze-thaw resistance of concrete. The spacing factor and specific surface can be measured in hardened concrete in accordance with ASTM C457 [11] and used to evaluate the size and distribution of air voids in hardened concrete. However, the testing is lab-intensive and time-consuming. Another disadvantage of ASTM C457 is that by the time the air void system is found inadequate, the structure has already been built and little can be done [12]. Consequently, it is crucial to determine the air void system quality in real-time while concrete is still fresh, and measures can be taken to ensure a good quality air void system or the concrete can be rejected. To improve the laboratory testing, Dansk Beton Teknik developed the Air Void Analyzer (AVA), which uses Stoke's law to measure bubble size distribution by timing the bubbles as they rise through a column of glycerol and water [13]. However, when implemented, the AVA equipment requires a series of precautions and is very sensitive and relatively expensive [14]. Because of these difficulties, AVA has not been widely adopted by state Departments of Transportation (DOTs) [13, 15].

The Super Air Meter (SAM), a test device recently developed by Dr. Tyler Ley, is a modified ASTM C231 Type B pressure meter gage and a restraint cage for safety purposes (Figure 1-1), which is capable of assessing air-void parameters, including total air content, spacing factor and specific surface of fresh concrete [16-17]. The major advantages of the SAM are that it employs an inexpensive piece of equipment like a pressure meter that most technicians are familiar with, and it is easily performed on the job site providing results in real-time. Meanwhile, a parameter called the SAM number has been proposed and correlated well to the spacing factor and freeze-thaw resistance of concrete. The SAM has been standardized under AASHTO TP118 [18]. It has the potential to serve as a quality control/quality assurance (QC/QA) tool for freeze-thaw resistance of concrete by state highway agencies.

The Tennessee Department of Transportation (TDOT) has no experience with the SAM meter and SAM number. TDOT is also concerned with the consistency of SAM number measurements and its suitability as a QC/QA tool. There is a need to examine the applicability of the SAM meter and SAM number to TDOT concrete mixes and determine the SAM number threshold for concrete with adequate freeze-thaw resistance in Tennessee.

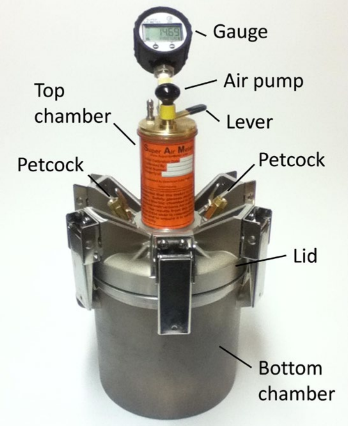


Figure 1-1. Super Air Meter (SAM) [17]

1.2 Objectives

The objectives of this study are to:

1. 1. Evaluate the applicability of the SAM meter and SAM number for TDOT concrete mixes.
2. Evaluate the consistency of the SAM number measurements for TDOT concrete mixes.
3. Determine the threshold of the SAM number for QA/QC purposes for TDOT concrete mixes.
4. Provide guidance/recommendations on the acceptable parameters for TDOT concrete mixes if the SAM test method is applicable in Tennessee.

The goals of the proposed research were achieved through comprehensive literature search and a state DOT survey, laboratory and field testing of fresh and hardened concrete mixes across Tennessee for typical SAM number values and freeze-thaw durability, statistical analysis of test results and correlations between the SAM number, other air-void parameters, and freeze-thaw resistance of concrete, determination of an appropriate SAM number as a QA/QC tool for TDOT concrete mixes.

1.3 Report organization

The rest of the report is organized as follows. Chapter 2 introduces the freeze-thaw damage and air void system of concrete, current test methods to investigate the freeze-thaw durability and air void parameters of fresh and hardened concrete, and the latest advances in the SAM test method and SAM number. Chapter 3 discusses the detailed methodology used to achieve the objectives of this study which involves state DOT surveying, field testing, and laboratory testing. In Chapter 4, the test results of field and laboratory concrete mixes are presented and analyzed; comprehensive statistical analyses were performed to evaluate the applicability and suitability of the SAM and to determine the appropriate threshold of the SAM number for TDOT concrete mixes. Chapter 5 concludes the study and makes recommendations on the implementation of the SAM in Tennessee. Appendix A summarizes the responses to DOTs survey. Appendix B briefly introduces the linear traverse method (LTM) for the calculation of air void parameters of hardened concrete.

Chapter 2 Literature Review

2.1 Freeze-thaw damage

Freeze-thaw damage is the most common deterioration type of concrete structures in cold climate regions. When the temperature drops below 0°C, the water in capillary pores of concrete freezes and forms into ice, accompanied by a 9% increase in volume, which usually results in expansion or hydraulic pressures [19]. Under repeated freeze-thaw cycles, concrete structures are permanently damaged, causing short service life and consequent costly maintenance work.

Although the exact mechanisms behind freeze-thaw damage are not entirely understood, it is believed that freezing water in the cement paste matrix causes a buildup of hydraulic pressure, osmotic pressure, or some combination of the two. The expansion of the freezing water compresses the remaining pore solution, and the pressure can only be alleviated if the remaining water escapes to empty space within or beyond the material's surface. However, the cement paste matrix resists water movement, leading to undesirable expansion of water as it freezes in the matrix. As a result, hydraulic pressure will increase, and cracks may occur in the matrix during the freezing. Additionally, due to water freezing out of the pore solution, a more concentrated solution of ions is created locally. This sets up a concentration gradient that causes the water to flow towards the freezing sites, leading to increased osmotic pressure and possibly cracking [5-7].

The air-void system in concrete plays a critical role in the resistance of concrete to freezing and thawing cycles by providing additional space to reduce internal pressure caused by frozen water. The air-void concrete system has been characterized by parameters including air content, spacing factor, specific surface [1, 8-9].

2.2 Air Content in Concrete

The American Concrete Institute (ACI) generally recommends a range of 3-8% entrained air by volume [20], as shown in Table 2-1, although the air volume required to prevent freeze-thaw damage varies based on the exposure conditions and the mix specifications.

TABLE 2-1 Air contents for frost-resistant concrete as recommended by ACI [20]

Nominal maximum aggregate size, in (mm)	Average air content, (%)	
	Severe exposure	Moderate exposure
3/8 (9.5)	7-1/2	6
1/2 (12.5)	7	5-1/2
3/4 (19.0)	6	5
1 (25)	6	5
1-1/2 (37.5)	5-1/2	6
3 (75)	4-1/2	3-1/2
6 (150)	4	3

2.3 Types of Air Void in Concrete

In hardened concrete, a void is an empty space in the cement paste that contains nothing but air. The type, size, shape, arrangement, and abundance of the voids are factors influencing the concrete properties, especially the freeze-thaw durability. The percentage of air-void volume is generally specified by the design of the mixture. Large quantities of small (most are not visible without magnification) air voids are desirable in concrete so that the average distance between any point in the paste and a void (spacing factor) is considerably short and, thus, the paste is protected from freezing and thawing. However, spacing factors much less than the maximum ensuring protection from freezing and thawing are counterproductive and should be avoided in that voids weaken the strength of concrete. Generally, the overall void content system in concrete is composed of two common types of voids: (1) entrained air voids and (2) entrapped air voids [21].

Entrained air voids, intentionally created by air-entraining admixture (AEA), are small spherical voids to protect the hardened concrete against the destructive forces of freezing and thawing. Entrained air voids generally range from 10 μm up to 1 mm in size [21]. Figure 2-1 shows the hardened cement paste with 0% and 0.4% AEA respectively [22].

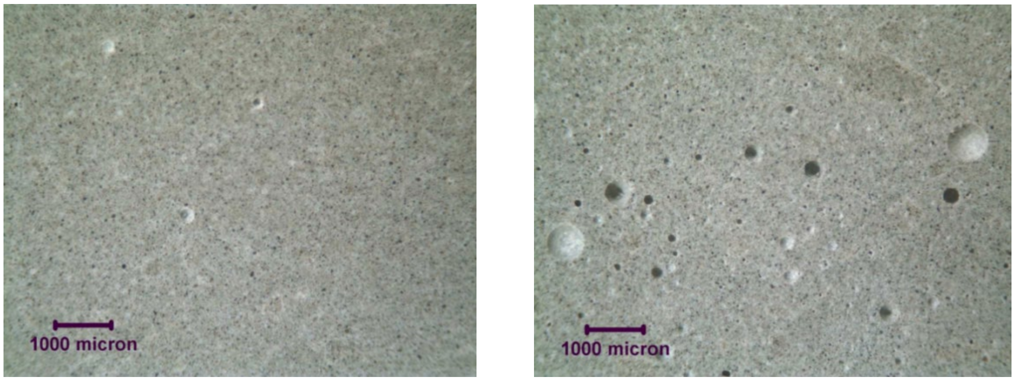


Figure 2-1. Hardened cement pastes with 0% and 0.4% AEA [22]

Entrapped voids are usually larger than 1 mm in size. They are irregular in spacing and shape and are too large and disconnected to provide any freeze-thaw resistance [21]. They also cause a decrease in strength, but unlike entrained air voids, they cause an increase in permeability and porosity, making a mix more susceptible to the ingress of various salts, ions, and water. Entrapped air voids are most often introduced into the concrete through the various mixing procedures but can also result from poor consolidation. Additionally, mix designs with lower workability are more disposed to the formation of entrapped air voids. Proper compaction methods, such as rodding or vibration, should be used to reduce entrapped air levels [22].

2.4 Characterization Methods of Air Void System

Currently, there are some test methods existing to measure air content in both fresh and hardened concrete. ASTM C457 [11] provides three methods for petrographic analysis to quantify air content in hardened concrete. While petrographic results tend to be more accurate than those provided by fresh concrete tests, their results are not immediately available because they require the use of hardened samples which must be cut and polished prior to analysis. Some of the common field methods for quantifying the total air content in fresh concrete include the Pressure Method (ASTM C231) [10], the Volumetric Method (ASTM C173) [23], and the Gravimetric Method (ASTM C138) [24].

The Pressure Method (ASTM C231) has been commonly used in the concrete industry to measure the air content of fresh concrete. Although it is easy and convenient to finish the test on the job site, the information on the air void size and distribution cannot be obtained. For the freeze-thaw durability of concrete structures, the air void size and distribution are more important than air content. To address the above issue, ASTM C457 can be used to acquire the spacing factor and specific surface of air voids in hardened concrete. However, this test is lab-intensive and time-consuming. Furthermore, because this test is performed on the hardened concrete, the obtained results lag behind the construction schedule of fresh concrete in the field [12]. Therefore, it is essential to measure the air void system of fresh concrete in real-time. The Air Void Analyzer (AVA), developed by a Danish company (Dansk Beton Teknik), can be used to measure the spacing factor and specific surface of fresh concrete based on the Stoke's law [13]. But this test device is relatively expensive and very sensitive, which is not suitable for field applications. Due to above disadvantages, the AVA has rarely been used by state DOTs [13, 15].

Recently, a new test device called Super Air Meter (SAM), has been developed by Dr. Tyler Ley to measure the air void size and distribution of fresh concrete in real-time. SAM is a modified version of ASTM C231 Type B pressure meter with a digital gauge and six restraining clamps. In addition to being able to measure the air content of fresh concrete, a parameter called SAM number characterizing the air void size and distribution can also be ontained [16-17]. Moreover, this test device is similar to traditional pressure meter and inexpensive, thus is suitable for application on the job site. AASHTO TP118 [18] has been issued to standardize the SAM test. Therefore, it is promising for state highway agencies to adopt SAM as a QC/QA tool to ensure concrete has sufficient freeze-thaw durability.

2.5 Evaluation of Freeze-thaw Durability of Concrete

To evaluate the freeze-thaw durability of hardened concrete, the most straightforward way is to conduct the freeze-thaw test as per ASTM C666 [25] or AASHTO T161 [26] to determine the durability factor. However, the freeze-thaw test requires a long duration to complete. Also, the limited cabinet capacity is unsuitable for testing a relatively large number of specimens at one time. Moreover, the acquired test results seriously lag behind the concrete construction schedule. Another method to assess the freeze-thaw durability of hardened concrete is to acquire the air void parameters of hardened concrete according to ASTM C457 [11]. Based on the measured air void parameters, the freeze-thaw resistance can be evaluated. For example, concrete with a spacing factor below 0.2 mm is usually regarded as freeze-thaw durable [27]. ASTM C457 test method is much faster than the freeze-thaw test. Unfortunately, ASTM C457 test is also conducted on the hardened concrete. Therefore, the test results are unable to effectively guide the construction of fresh concrete in advance. Although an Air Void Analyzer (AVA) can determine the air void parameters of fresh concrete, the test device is very sensitive to vibration and thus is not suitable for QC/QA purposes in the field.

2.6 Relationship between Super Air Meter (SAM) Number and Freeze-thaw Durability

SAM testing involves three pressure steps with a maximum pressure of 310 kPa (45 psi), which was improved from the previous version, used five pressure steps with a maximum pressure of 517 kPa (75 psi). The SAM number is defined as the difference in the equilibrium pressure at the highest pressure (45 psi in the top chamber) between the first and second sequences [17], as illustrated in Figure 2-2.

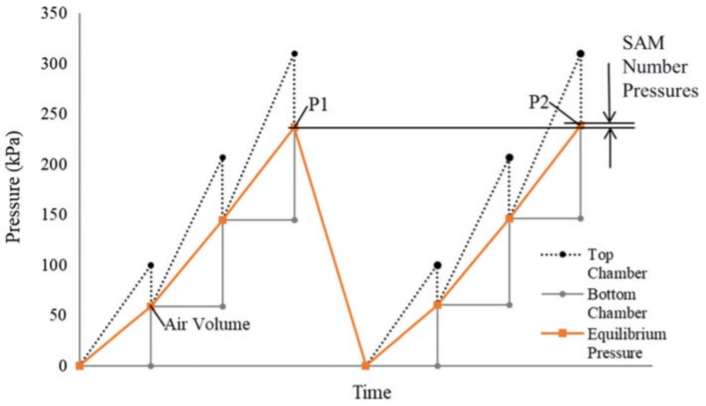


Figure 2-2. SAM Testing Procedure and SAM number [17]

Ley and Tabb [16] investigated the mechanism of the SAM test and revealed the rationale behind it is that when fresh concrete is compressed in sequential pressures, bubbles of different sizes would respond differently to these pressures. The larger bubbles (>0.008 in. or >0.20mm) would just be compressed under pressure and then return to their original size, while the smaller bubbles (<0.008 in. or <0.20mm) would dissolve in the surrounding solution. In theory, by understanding at what pressures these bubbles dissolve and applying different pressures, the bubbles' size and spacing could be indirectly estimated.

A lower SAM number correlates to a well-distributed air void system, defined by a low spacing factor and high specific surface [12, 16, 28]. Ley et al. [17] found that a SAM number of 0.20 and 0.25 shows a correlation to a spacing factor of 200 μm and 250 μm with an 88% and 85% agreement, respectively. The SAM number also shows a higher correlation to rapid freeze-thaw testing than current recommendations for the spacing factor, indicative of the potential advantage of SAM over the ASTM C457 method. The variability of the SAM number is comparable to other direct and indirect measurements of air void size and spacing. A SAM number of below 0.20 is typically expected to have an adequate air void system to be ideal in preventing freeze-thaw damage [12, 16-17, 28]. Todak [29] found that higher SAM numbers correlate to a lower critical degree of saturation and reduction in the estimated service life of the concrete.

Riding and Albahttiti [30] used SAM as a concrete quality control test. They found that the SAM number had a 154% higher coefficient of variation per site than the total air content. They also found that there is a correlation between the air content and the SAM number. The data from the study at the Federal Highway Administration's Turner Fairbank Highway Research Center

Laboratory showed that the SAM test of fresh concrete was able to provide an indication of air void adequacy in low-slump air-entrained concrete [12]. Generally, water-reducing admixtures often affect the quality of the air void system. If the total air volume is kept constant, a system with water-reducing admixtures is expected to have a lower SAM number or a higher spacing factor than a similar system without a water reducer [29].

In 2019, Dąbrowski et al. [31] investigated the suitability of the SAM to evaluate the quality of air void system in concrete based on laboratory-produced mixes and on-site trial mixes. The test results confirmed the correlation between the SAM number in fresh concrete and the spacing factor in hardened concrete. The criterion of the SAM number $\leqslant 0.4$ was proposed to predict the target microvoids content $A_{300} \geqslant 1.5\%$ in hardened concrete.

In 2020, Hall et al. [32] compared the SAM number and spacing factor from lab and field concrete mixtures. It was found that 25% of field concrete had a spacing factor higher than the recommended values of 0.2 mm. There was a good correlation between a SAM number of 0.20 and a spacing factor of 0.2 mm for both lab and field concrete mixtures.

In 2021, Becker et al. [33] showed that SAM number is closely related to the spacing factor of hardened concrete and could be used to determine the efficiency of the air void system.

Chapter 3 Methodology

3.1 DOTs survey

To obtain the latest advances in studies and applications of the SAM test and SAM number, a nationwide survey to state Departments of Transportation (DOTs) regarding their adoption of the SAM meter and SAM number in their specifications was conducted. Questionnaires were carefully developed by the research team in collaboration with TDOT engineers and then sent to all the state DOTs in the US. The acceptance criteria and the threshold for adequate freeze-thaw resistance of concrete were surveyed, and the results were analyzed to obtain the successful experience from other states as well as lessons from past failed cases. The responses to DOTs survey are summarized in Appendix A.

3.2 Identification of concrete construction projects

To perform the SAM test on the concrete mixes throughout Tennessee, the concrete field construction projects were identified first. The research team made an effort to identify as many projects as possible by cooperating with TDOT Materials and Tests Division engineers so that a relatively large number of concrete mixes across Tennessee were included in the study. The information about each project, such as the locations of the projects, the mix designs of concrete, the raw materials used to make concrete, etc., were obtained. This way, a statistical analysis was performed on the test results, and reasonable conclusions were drawn about the applicability of the SAM meter and SAM number to TDOT concrete mixes. When collecting information about field construction projects, different factors including concrete type in TDOT specifications (e.g., Class A, Class D, etc.), project location (e.g., Region 1, 2, 3, and 4 of Tennessee), raw materials of concrete (e.g., aggregate, chemical admixtures, etc.) were considered to cover as many concrete mixes as possible.

3.3 Field Testing of Fresh Concrete Mixes

Once the concrete construction projects had been identified, each of them was visited by the research team during the construction period. On the job sites, the research team performed the SAM test on the fresh concrete mixes to obtain the total air content and SAM number of the concrete. Concrete specimens (prisms) were fabricated on the job site for future laboratory testing (e.g., for the ASTM C457 air content, spacing factor, and specific surface, and the ASTM C666/AASHTO T161 durability factor). In addition, raw materials of the concrete mixes such as coarse and fine aggregate, cement, mineral and chemical admixtures were collected from the concrete plants. These concrete specimens and raw materials were shipped to the University of Tennessee–Knoxville (UTK) for future laboratory testing.

3.4 Laboratory Testing of Fresh and Hardened Concrete Samples

3.4.1 Laboratory Testing of Hardened Concrete Samples fabricated on the job site

The fabricated concrete specimens on the job site were cured in the standard curing room (23.0 ± 2°C, and relative humidity greater than 95%) in the laboratory following ASTM C192 [34]. After 24 hours, the specimens were demolded and then continued to be cured until the 28th day. Afterward, all field specimens were subject to an air void parameters (ASTM C457) test, while

10 out of 14 field specimens were subject to a freeze-thaw durability (ASTM C666 [25] or AASHTO T161[26]) test.

3.4.2 Making concrete mixes and testing of fresh and hardened concrete in the lab

There are many factors that affect the air void system and freeze-thaw durability of concrete, such as aggregate quality, air-entraining admixture (AEA) type and dosage, cement, and supplementary cementitious materials (SCMs, e.g., fly ash) content, water/(cement+SCMs) ratio, etc. In order to evaluate the applicability of SAM meter to various concrete mixes and determine the threshold of the SAM number for concrete with adequate freeze-thaw resistance in Tennessee, raw materials collected from the qualified concrete plant in each Region were used to produce concrete mixes in the lab and carry out related tests to obtain enough data. The purpose of the lab test plan is to investigate the sensitivity of the SAM to the air void system of fresh concrete mixes by adjusting one or two mix parameters when keeping other variables/conditions the same; the dosage of AEA was adjusted to change the air void system. Based on field testing of fresh concrete mixes, the most commonly used classes of concrete work for TDOT are Class A and Class D. Therefore, the mix design of Class A and Class D, and raw materials (e.g., aggregates, cement, fly ash, and chemical admixtures, etc.) were acquired from the qualified concrete plant in Region 1, 2, 3, and 4 of Tennessee.

The fresh concrete mixes were made using a mixer with a capacity of 3 cubic feet in the laboratory according to ASTM C192 [34]. Immediately after mixing, the slump test was conducted as per ASTM C143 [35], and air content and SAM number were measured as per AASHTO TP118 [18]. After the completion of each concrete mixes test, duplicate cylinder specimens for compressive strength test and one prism specimen were cast for ASTM C457 test respectively for each/all concrete mixes. Due to limited cabinet capacity and long duration for the ASTM C666 freeze-thaw test, duplicate prism specimens were cast for partial concrete mixes. It is worth mentioning that the ASTM C457 test (spacing factor) is usually used to evaluate the freeze-thaw durability of the concrete mixture instead of the ASTM C666 freeze-thaw test.

The casted specimens were cured in the standard curing room (23.0 ± 2°C, and relative humidity greater than 95%) following ASTM C192. After 1 day, the specimens were demolded and continued to be cured until the 28th day. Afterward, the specimens were subject to the following tests.

(1) Compressive strength (ASTM C39) test

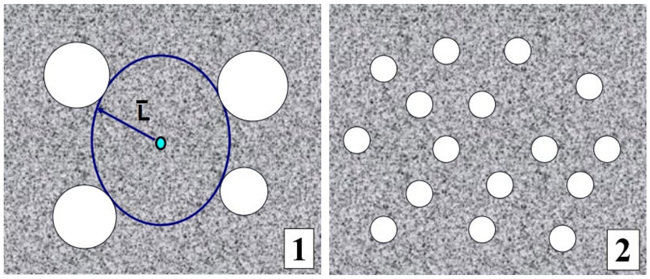
The 28-day compressive strength test was conducted on the 4×8 in. cylinder specimens using a compression machine with a load capacity of 500 kips (2224 KN). The loading rate was about 400-500 lb/sec (equivalent to 33-41 psi/sec) in accordance with ASTM C39 [36]. Prior to testing, the two end faces of the test specimen were polished to make sure they were flat and level. Elastomeric bearing pads and steel retainers were used to evenly distribute the compressive load forces.

(2) Air void parameters (ASTM C457) test

For hardened concrete, the most commonly used air void parameters are air content, spacing factor, and specific surface.

Air content is the percentage of the volume of air voids in the total volume of the concrete mixture. Air voids in concrete can be divided into two categories: entrapped air and entrained air. Entrapped air is the natural air produced during the mechanical mixing of the fresh concrete mixture. The size of entrapped air voids is usually larger than 1 mm. Entrained air is the air bubbles intentionally created by AEA. The size of entrained air voids is typically between 10 μm and 1 mm.

The spacing factor is a parameter intended to represent the maximum distance in the cement paste from the periphery of an air void, as shown in Figure 3-1 (a). From the perspective of freeze-thaw damage, the spacing factor is related to the maximum distance that water/ice would have to travel in the cement paste to reach an air void to relieve the hydraulic and osmotic pressures caused by the expansion of water during the freezing conditions [37]. Therefore, a lower spacing factor means the concrete mixture has a higher resistance against freeze-thaw damage. In general, the desired spacing factor for the concrete mixture with enough freeze-thaw resistance is less than 0.2 mm (200 μm). It is worth mentioning that the spacing factor is usually used to evaluate the freeze-thaw resistance of the concrete mixture due to limited cabinet capacity and long duration for the ASTM C666 freeze-thaw test. For hardened concretes with the same air content, their spacing factors may be very different, as shown in Figure 3-1 (a) and (b).



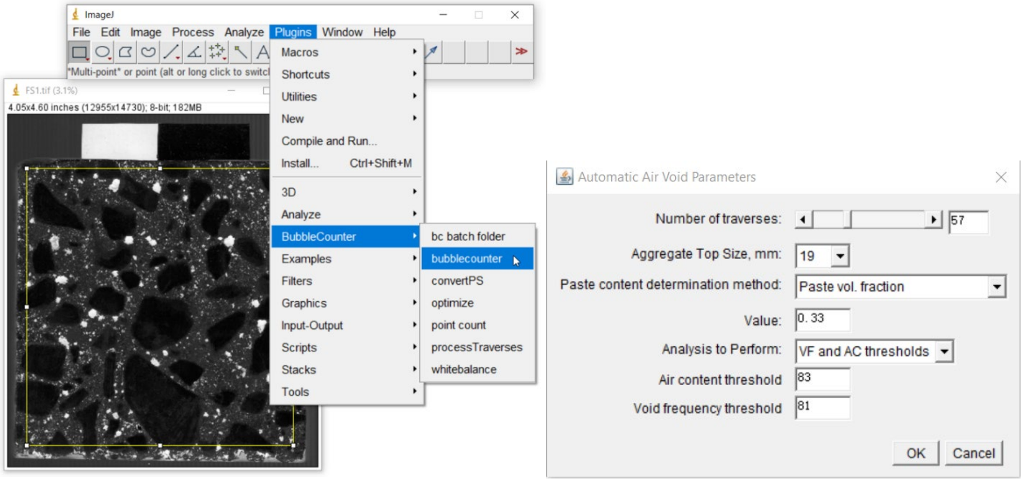
(a) (b)

Figure 3-1. Same air content with different spacing factors [38]

Specific surface is the surface area of air voids divided by their volume. Compared with air content and spacing factor, the specific surface is less commonly used.

The calculation principle of air void parameters is the linear traverse method (LTM) [11, 39], briefly introduced in the Appendix B.

In this study, the ASTM C457 Procedure C was used to determine the air void parameters of hardened concrete. The 100×100×10 mm specimens cut from the center of 100×100×400 mm prisms were carefully polished by successively finer silicon carbide sandpapers including No. 220, 320, 400, 600, 800,1000, 1200, 1500, and 2000 grit sizes to ensure their surfaces were flat and smooth. Then the specimen surfaces were painted black by drawing overlapping parallel lines with a wide-tipped black permanent marker (e.g., Sharpie magnum). After the surfaces dried, the white barium sulfate ($BaSO_4$) powders with a particle size of 1 to 4 μm were pressed into the voids using a rubber stopper. The excess $BaSO_4$ powders on the surfaces were scraped by a sharp blade, and the last remnants of $BaSO_4$ powder on the surface were removed with a very lightly oiled finger. Afterward, any voids in the aggregate were colored black with a fine-tipped black permanent marker under an optical microscope, so they did not register as entrained air in the later analysis process. The specimens were scanned at a resolution of 3200 dpi with a high-resolution flatbed scanner. The ImageJ software [40] supplemented with the Bubblecounter macro [41] was used to analyze the acquired specimen surface images to obtain the air void parameters as shown in Figure 3-2, following the method described by Peterson et al. [42-46].



Number of traverses: 57

Aggregate Top Size, mm: 19

Paste content determination method: Paste vol. fraction

Value: 0. 33

Analysis to Perform: VF and AC thresholds

Air content threshold 83

Void frequency threshold 81

Figure 3-2. Air void parameters test

(3) Freeze-thaw durability (ASTM C666) test

The freeze-thaw durability of hardened concrete was tested as per ASTM C666 [25]. After 28 days of curing, the 75×100×400 mm prism specimens were submerged in water for 48 h to achieve saturation. Then the specimens were removed, and the initial saturated-surface-dry mass and fundamental transverse frequency were determined by a scale and the James E-Meter, respectively. After that, the specimens were subject to rapid freezing and thawing cycles in water. A Freeze-thaw cycle consisted of lowering the temperature of the specimens from 40 to 0 °F [4 to -18 °C] and raising it from 0 to 40 °F [-18 to 4 °C] in around 4 hours. During the test, the surface-dried masses and fundamental transverse frequencies of specimens were tested at every 25 cycles. The specimen is considered as a failure when either the test reaches 300 total cycles, or its relative dynamic modulus of elasticity reaches 60% of its initial modulus, or its mass loss reaches 5% of its initial mass, whichever occurs first. The durability factor (DF), the most critical parameter, was used to characterize the freeze-thaw resistance of concrete at the end of the freeze-thaw test, and it can be calculated by the following formula:

$$DF = (P \times N)/M$$

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 the exposure is to be terminated, whichever is less.

M = Specified number of cycles at which the exposure is to be terminated (usually 300 cycles).

P is determined as follows.

$$P=(n_c^2/n^2)\times 100$$

P = Relative dynamic modulus of elasticity after specific cycles of freezing and thawing.
n = fundamental transverse frequency at 0 cycles of freezing and thawing.
n_c = fundamental transverse frequency at c cycles of freezing and thawing.

Due to limited cabinet capacity and long duration for the ASTM C666 freeze-thaw test, duplicate prism specimens were cast for partial concrete mixes. It is worth mentioning that the ASTM C457 test (spacing factor) is usually used to evaluate the freeze-thaw resistance/durability of the concrete mixture instead of the ASTM C666 freeze-thaw test. Therefore, all lab specimens were subject to the air void parameters (ASTM C457) test.

3.5 Field Testing of Fresh Concrete Mixes Using AVA

The state-of-the-art laboratory testing devices, including AVA and the SAM meter from Federal Highway Administration Mobile Concrete Trailer (MCT) were loaned to UTK during the research duration of the study. Tentatively, the AASHTO TP75 (AVA test) and AASHTO TP118 (SAM test) on fresh concrete mixes were conducted on a construction site. In addition, the specimens were fabricated on the job site for future air void parameters (ASTM C457) test and ASTM C666 freeze-thaw test in the lab.

3.6 Statistical Analyses

The research team performed a comprehensive statistical analysis on the test results to evaluate the consistency of the SAM number for TDOT concrete mixes. Based on the results from the statistical analyses, the suitability of the SAM as a QC/QA tool was determined. The research team also correlated the SAM number to the spacing factor obtained from ASTM C457 as well as to the durability factor from ASTM C666/AASHTO T161. The SAM number was examined in its capability of characterizing the air-void system and reflecting the resistance of concrete to freezing and thawing cycles. Then the applicability of SAM to TDOT concrete mixes was determined.

3.7 Conclusions and Recommendations

Based on the results and findings from this study, conclusions were summarized, and recommendations were made to TDOT specifications regarding the application of the SAM for TDOT concrete mixes. The acceptance criteria were established and recommended to TDOT for adoption in its specifications.

Chapter 4 Results and Discussion

In this chapter, the test results of 14 field concrete mixes were first summarized and analyzed individually. Then the test results of 66 lab concrete mixes were presented and analyzed. Next, test results of field concrete mixes utilizing the Super Air Meter (SAM) and Air Void Analyzer (AVA) from Federal Highway Administration (FHWA) Mobile Concrete Trailer (MCT) are presented and analyzed. Finally, comprehensive statistical analyses were performed on the test results from 14 field concrete mixes and 66 lab concrete mixes.

4.1 Test results of field concrete mixes

A total of 14 field tests on fresh concrete mixes were conducted in Region 1, 2, 3, and 4 of Tennessee using the SAM. The mix designs of concrete mixes in the field from each Region are listed in Table 4-1.

TABLE 4-1. Mix design of field concrete mixes in Tennessee

Region	1	1	1	1	2	2	2
Class of concrete	SCC	Precast	Class D	Class A	Class A	Class A	Class A
	lb/yd^3	lb/yd^3	lb/yd^3	lb/yd^3	lb/yd^3	lb/yd^3	lb/yd^3
Cement	800 (Type I)	705 (Type III)	520 (Type I)	423 (Type I)	485 (Type I)	564 (Type I)	423 (Type I)
Fly ash	0	0	110	141	125	0	141
GGBFS	0	0	0	0	0	0	0
Silica fume	0	0	0	0	0	0	0
Coarse aggregate	1440 (CS#7)	1780 (CS#67)	1850 (SG#57)	1800 (CS#57)	1830 (CS#57)	1815 (CS#57)	1815 (CS#57)
Fine aggregate	1440 (MS)	1482 (MS)	1180 (NS)	1398 (MS)	1225 (NS)	1240 (NS)	1210 (NS)
Water	295	275	250	253	242	250	250
Chemical admixtures	1,2,3, 4,5	3,5	1,2	1,2,3, 4,5	1,5	1, 2, 3, 4	1, 2, 3, 4, 5
Design w/cm ratio	0.37	0.39	0.40	0.45	0.40	0.44	0.44
Design air content	6%	0%	7%	6%	6%	6%	6%

Table 4-1. Mix design of field concrete mixes in Tennessee (continued)

Region	3	3	3	3	4	4	4
Class of concrete	Class D	Class A	Class D	Class A	Class D	Class A	Class CP
	lb/yd^3	lb/yd^3	lb/yd^3	lb/yd^3	lb/yd^3	lb/yd^3	lb/yd^3
Cement	465 (Type I)	423 (Type I)	465 (Type I)	564 (Type I)	465 (Type I)	474 (Type I)	420 (Type I)
Fly ash	155	141	155	0	155	90	140
GGBFS	0	0	0	0	0	0	0
Silica fume	0	0	0	0	0	0	0
Coarse aggregate	1815 (CS#57)	1835 (CS#57)	1815 (CS#57)	1800 (CS#57)	1600 (SV#5)	1758 (CS#57)	650 (CS#4) 1110 (CS#57)
Fine aggregate	1170 (NS)	1250 (NS)	1170 (NS)	1261 (NS)	1151 (NS)	1340 (NS)	1320 (NS)
Water	250	250	250	250	248	236	250
Chemical admixtures	1,2,3, 4,5	1,2,3, 4,5	1,2	1,2	1,2,5	1, 3	1, 2
Design w/cm ratio	0.40	0.44	0.40	0.44	0.40	0.42	0.45
Design air content	7%	6%	7%	6%	7%	6%	5%

Note:
SCC-self consolidating concrete
Precast-precast/prestress concrete bridge member
CS-Crush stone
SG-Surf.concgranit (surface granite aggregate)
SV-Surf.concgravel (surface gravel aggregate)
MS-manufactured sand
NS-natural sand
Chemical admixtures:
1-Air entraining admixture (AEA)
2-Reducer
3-Reducer/Retarder
4-Accelerator
5-High range water reducer (HRWR)
Retarder to be used when the temperature is 85 degrees F or higher.
Admixture dosage shall be in accordance with the manufacturer's recommendations.

For chemical admixtures as shown in Table 4-1, the air entraining admixture (1), reducer (2), and/or high range water reducer (3) are usually used for TDOT concrete mixes. Based on the information from several quality control managers of qualified concrete plant in different regions, retarders (3) and/or accelerators (4) are optional: they are only used if the contractor request/order them, but most of the time (95% or more) they are not used or requested for TDOT concrete. Also, the most commonly used class of concrete for TDOT are Class A and Class D (Class A is more commonly used than Class D).

Table 4-2 summarizes the test results of field concrete mixes in Region 1, 2, 3, and 4 of Tennessee. All field concrete mixes were subject to air void parameters (ASTM C457) test, while 10 out of 14 field mixes were subject to freeze-thaw durability (ASTM C666/AASHTO T161) test.

TABLE 4-2. Test results of field concrete mixes in Tennessee

No.	Region	Class of concrete	SAM test		ASTM C457 test			ASTM C666 test
			Air content (%)	SAM number	Air content (%)	Spacing factor (mm)	Specific surface (mm^{-1})	Durability Factor (%)
1	1	SCC	7.0	0.09	8.3	0.168	23.6	92.13
2	1	Precast	2.8	0.58	1.3	0.659	14.0	34.35
3	1	Class D	5.6	0.15	6.3	0.172	24.9	91.25
4	1	Class A	4.1	0.40	3.2	0.483	11.9	39.51
5	2	Class A	4.6	0.38	3.3	0.267	21.7	73.19
6	2	Class A	4.7	0.37	4.1	0.313	16.2	N/A
7	2	Class A	5.1	0.26	5.4	0.178	25.6	N/A
8	3	Class D	6.5	0.31	5.8	0.166	27.3	87.12
9	3	Class A	5.7	0.19	5.2	0.164	30.6	90.51
10	3	Class D	6.8	0.07	8.2	0.153	21.3	95.87
11	3	Class A	4.8	0.46	3.1	0.221	26.1	62.40
12	4	Class D	6.5	0.13	7.4	0.081	45.0	97.43
13	4	Class A	6.4	0.10	7.5	0.122	27.3	N/A
14	4	Class CP	4.5	0.40	3.8	0.364	14.7	N/A

It is clear that 14 field concrete mixes had different SAM numbers in various regions, even though they were the same class of concrete (e.g., Class A, Class D). This indicates there is no good consistency of SAM numbers in different locations, even if concrete mixes belong to the same class. The SAM number indicates the quality of the air void system in concrete mixes [17]. The discrepancy in SAM numbers of concrete in different regions actually reflected the difference in the air void system of concrete.

To better analyze the test results from field concrete mixes, Figure 4-1 through Figure 4-7 were plotted.

Figure 4-1 shows the air content of fresh concrete mixes versus the freeze-thaw durability factor (DF) of hardened concrete. The durability factor (DF) of 60% is usually regarded as the failure limit for the freeze-thaw test, while the DF between 60% and 80% is considered unsatisfactory, and the DF above 80% is considered satisfactory [47-48].

Among these 10 concrete mixes, only one is non-air-entrained concrete, which had an air content of 2.8% at fresh state. The freeze-thaw durability factor of this concrete was 34.35%, much lower than the failure limit of 60%. This confirmed that the non-air-entrained concrete is prone to freeze-thaw damage. The rest of the 9 concrete mixes had an air content of 4%-8%, and the freeze-thaw durability factor was higher than that of non-air-entrained concrete. This was because the intentionally introduced air voids in concrete can provide reservoirs to alleviate the hydraulic and osmotic pressures induced by the freezing water into ice. However, although the air content of 9 concrete mixes met TDOT specification (e.g., 4%~8% for Class A, 4.5%~7.5% for

Class D), the freeze-thaw durability factor varied widely: one concrete mixes had a DF of 39.51%, indicating poor freeze-thaw resistance; 2 concrete mixes had DF between 60% and 80%, showing unsatisfactory freeze-thaw resistance; 6 concrete mixes had DF higher than 80%, showing satisfactory freeze-thaw resistance.

Therefore, it is concluded that only the air content requirement for fresh TDOT concrete mixes does not necessarily guarantee enough freeze-thaw resistance.

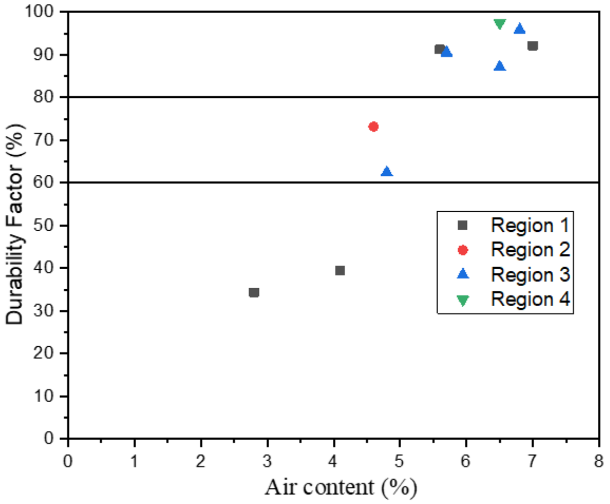


Figure 4-1. Air content of fresh concrete versus durability factor of hardened concrete

Figure 4-2 shows the air content of fresh concrete mixes versus the SAM number of fresh concrete mixes. A low SAM number indicates a good air void system in fresh concrete mixes [12, 16, 28]. The non-air-entrained fresh concrete with an air content of 2.8% had a SAM number of 0.58. 5 concrete mixes with an air content of 4%~5% had a SAM number between 0.35 and 0.5. In addition, 8 concrete mixes with an air content of 5%~8% had a SAM number below 0.31, and 6 of them had a SAM number below 0.2. Overall, an increase in air content caused a decrease in the SAM number, and thus a better air void system in fresh concrete mixes.

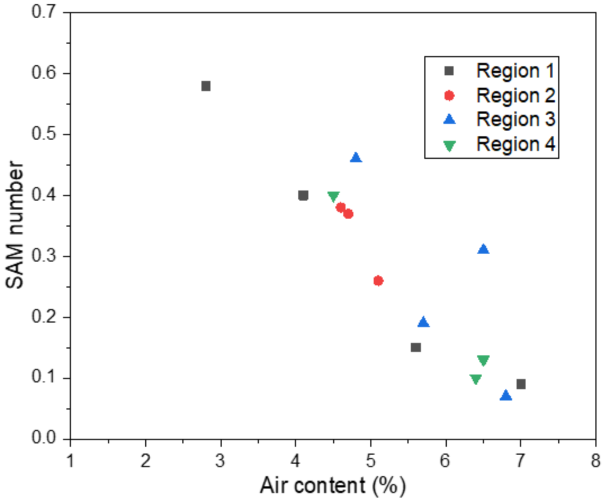


Figure 4-2. SAM number versus air content of fresh concrete

Figure 4-3 shows the air content of fresh concrete mixes versus the spacing factor of hardened concrete. A lower spacing factor is desired for good freeze-thaw durability. ACI 201suggests that the spacing factor in concrete should be 0.2mm (0.008in) or below for enough freeze-thaw durability [27]. This limit is shown in Figure 4-3 with a horizontal line.

The non-air-entrained concrete with an air content of 2.8% had a spacing factor of 0.659 mm, much higher than the recommended limit, indicating a poor air void system in hardened concrete. The rest of the 13 concrete mixes had an air content of 4%-8%, and the spacing factor was lower than that of non-air-entrained concrete. Three concrete mixes with an air content of 4%~5% had a spacing factor between 0.3 mm and 0.5 mm, much higher than the limit 0.2 mm suggested by ACI 201, showing an unsatisfactory air void system. Two concrete mixes with an air content of 4%~5% had a spacing factor between 0.2 mm and 0.3 mm. Eight concrete mixes with an air content of 5%-8% had a spacing factor below 0.2 mm, indicating a satisfactory air void system. Therefore, although the air content of 13 concrete mixes met TDOT specification, the air void system in hardened concrete showed different quality. Thus, it is concluded that the air content requirement in TDOT specification does not necessarily ensure that TDOT concrete mixes have the high quality of air void system.

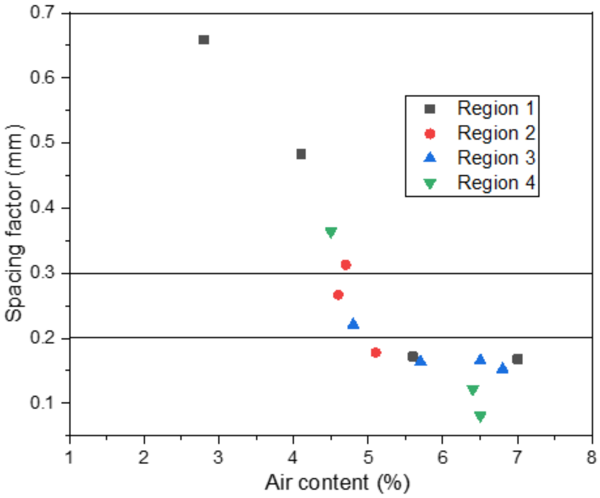


Figure 4-3. Air content of fresh concrete versus a spacing factor of hardened concrete

Figure 4-4 shows the air content of fresh concrete versus the air content of hardened concrete. It was found that compared with fresh concrete, the air content was higher or lower in hardened concrete. There is no equal relationship between the air content of fresh concrete and hardened concrete [49-50]. This discrepancy could be caused by many factors such as air voids stability in plastic concrete, placement, and consolidation [39]. Furthermore, this discrepancy can also increase due to the various test methods for taking a measurement of air content in fresh and hardened concrete [51].

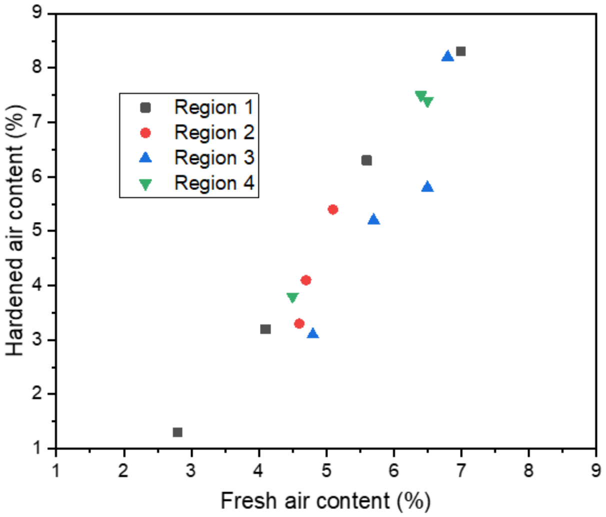


Figure 4-4. Air content of fresh concrete versus air content of hardened concrete

Figure 4-5 shows the spacing factor of hardened concrete mixes versus the freeze-thaw durability factor (DF) of hardened concrete. Six concrete mixes had a spacing factor lower than 0.2 mm, and their DF was higher than 80%, indicating satisfactory freeze-thaw durability. Two concrete mixes had a spacing factor between 0.2 mm and 0.3 mm, and their DF was between 60% and 80%, showing unsatisfactory freeze-thaw resistance. Two concrete mixes had a spacing factor higher than 0.4 mm, and their DF was lower than 60%, showing poor freeze-thaw durability.

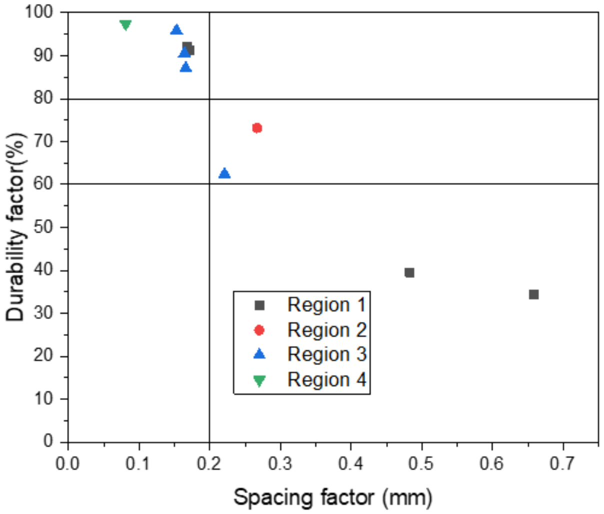


Figure 4-5. Spacing factor versus durability factor of hardened concrete

Figure 4-6 shows the SAM number of fresh concrete mixes versus freeze-thaw durability factor (DF) of hardened concrete. It was obvious that 5 concrete mixes had a SAM number lower than 0.2, and their DF was higher than 90%, displaying enough freeze-thaw resistance. One concrete mix with a SAM number of 0.31 had a DF of 87.12%, indicating good freeze-thaw resistance. The other 4 concrete mixes with a SAM number higher than 0.38 had a DF lower than 80% or even 60%, showing unsatisfactory or even poor freeze-thaw durability. Obviously, the DF decreased with the increase of the SAM number.

From a conservative perspective, 0.2 can be used as the threshold value of the SAM number to ensure TDOT concrete mixes have satisfactory freeze-thaw resistance.

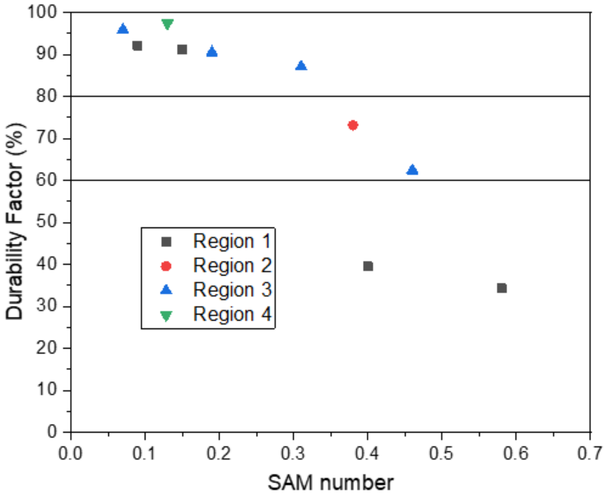


Figure 4-6. SAM number versus durability factor of hardened concrete

Figure 4-7 shows the SAM number of fresh concrete mixes versus the spacing factor of hardened concrete. Eight concrete mixes had a spacing factor below 0.2 mm, while 6 of them had a SAM number lower than 0.2 and 2 of them had a SAM number higher than 0.2. The other 6 concrete mixes had a spacing factor above 0.2 mm, and their SAM number was also higher than 0.2. The increase of SAM number resulted in the increase of spacing factor.

A spacing factor of 0.2 mm was used as the limit, as plotted in Figure 4-7 with a horizontal line, and a SAM number of 0.2 was selected as the threshold, as shown in Figure 4-7 with a vertical line. It is clear that the data in Figure 4-7 were separated into four quadrants. The SAM number correlated well with the spacing factor in a lower left quadrant and upper right quadrant: the lower left quadrant indicates satisfactory air void systems, while the upper right quadrant indicates unsatisfactory air void systems. The SAM number did not agree well with the spacing factor in the upper left quadrant and lower right quadrant. A SAM number of 0.2 showed a correlation to a spacing factor of 0.2 mm with 86% agreement (12 out of 14 concrete mixes).

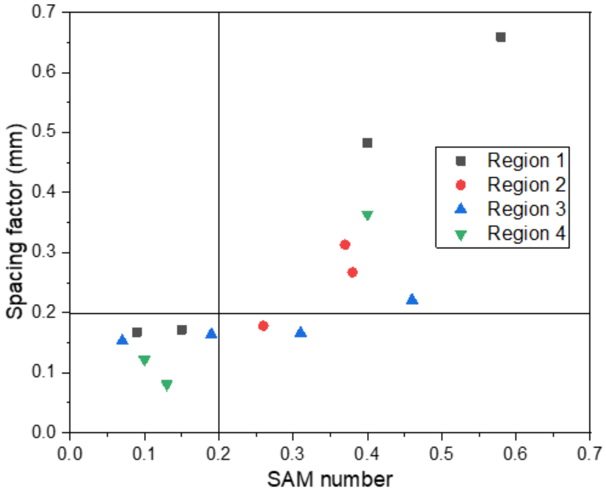


Figure 4-7. SAM number versus spacing factor of hardened concrete

4.2 Test results of lab concrete mixes

4.2.1 Test results of lab concrete mixes made using raw materials from Region 1

At the beginning of this study, two trial concrete mixes, including one non-air-entrained concrete and one air-entrained concrete, were produced using raw materials from Region 1 in the lab. The mix design data are summarized in Table 4-3. These two trial concrete mixes do not belong to any class of TDOT concrete mixes.

TABLE 4-3. Mix design data of trial concrete mixes

RAW MATERIALS	lb/yd^3
CEMENT (TYPE I)	520
FLY ASH (Class F)	0
GGBFS	0
SILICA FUME	0
CRUSH STONE #57	1821
MANUFACTURED SAND	0
NATURAL SAND	1272
WATER	347
AEA (MasterAir AE 90)	0, 6 oz
DESIGN W/CM RATIO	0.67
DESIGN AIR CONTENT	0, 6%

Test results of two concrete trial mixes such as air content and SAM number of fresh concrete, air content, spacing factor, specific surface, and durability factor of hardened concrete are summarized in Table 4-4.

TABLE 4-4. Test results of trial concrete mixes

Number	Variables (AEA dosage) oz/yd^3	SAM test		ASTM C457 Test			ASTM C666 Test
		Air content (%)	SAM number	Air content (%)	Spacing factor (mm)	Specific Surface (mm^{-1})	Durability Factor (%)
1	0	1.60	0.42	2.10	0.514	14.2	13.29
2	6	4.40	0.07	4.90	0.097	51.6	86.04

The mix design data of Class D concrete provided by the qualified concrete plant in Region 1 are shown in Table 4-5.

TABLE 4-5. Mix design data of Class D concrete (Region 1)

CLASS of CONCRETE	Class D lb/yd^3
CEMENT (TYPE I)	520
FLY ASH (Class F)	110
GGBFS	0
SILICA FUME	0
SURF.CONCGRANIT #57	1850
MANUFACTURED SAND	0
NATURAL SAND	1180
WATER	250
AEA (MasterAir AE 90)	5 oz
HRWR (MasterGlenium 7920)	25 oz
DESIGN W/CM RATIO	0.4
DESIGN AIR CONTENT	7%

During the research duration of the study, number 1 to 8 in Table 4-6 were produced. For these mixes, the dosage of AEA was adjusted (increased or decreased) to change the air void system, but other variables/conditions were kept the same.

The number 1 is the same as the mix design provided by the concrete plant, and the 2nd to the 8th were changed by the dosage of AEA. Immediately after mixing, the resultant slump, air content, and SAM number were tested as per ASTM C143 and AASHTO TP118. The test results are summarized in Table 4-6.

TABLE 4-6. Slump and SAM test results of fresh Class D concrete (Region 1)

Number	Variables (AEA dosage, oz/yd^3)	Test results		
		Slump (inch)	Air content (%)	SAM number
1	5.0	7	5.9	0.22
2	5.2	7	6.2	0.25
3	5.4	7	6.4	0.19
4	5.6	7	6.5	0.08
5	5.8	7.25	6.9	0.15
6	4.8	7	5.7	0.31
7	4.6	7	5.6	0.17
8	4.4	7	5.0	0.29

Note: The slump was reported to the nearest 0.25 inch based on ASTM C143.

The SAM test results are shown in Figure 4-8.

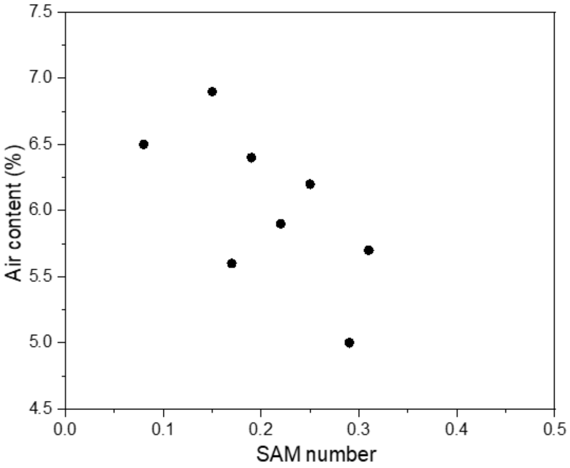


Figure 4-8. SAM test results of fresh Class D concrete (Region 1)

The mix design data of Class A concrete provided by the qualified concrete plant in Region 1 are shown in Table 4-7.

TABLE 4-7. Mix design data of Class A concrete (Region 1)

CLASS of CONCRETE	Class A lb/yd^3
CEMENT (TYPE I)	423
FLY ASH (Class F)	141
GGBFS	0
SILICA FUME	0
CRUSH STONE #57	1800
MANUFACTURED SAND	1362
NATURAL SAND	0
WATER	254
AEA (MasterAir AE 90)	3 oz
HRWR (MasterGlenium 7920)	18 oz
DESIGN W/CM RATIO	0.45
DESIGN AIR CONTENT	6%

During the research duration of the study, number 9 to 16 in Table 4-8 were produced. For these mixes, the dosage of AEA was adjusted (increased or decreased) to change the air void system, but other variables/conditions were kept the same.

The number 9 is the same as the mix design provided by the concrete plant, and the 10th to the 16th were changed by the dosage of AEA. Immediately after mixing, the resultant slump, air content, and SAM number was tested as per ASTM C143 and AASHTO TP118, as summarized in Table 4-8.

TABLE 4-8. Slump and SAM test results of fresh Class A concrete (Region 1)

Number	Variables (AEA dosage, oz/yd^3)	Test results		
		Slump (inch)	Air content (%)	SAM number
9	3.0	5	4.6	0.37
10	3.2	5	4.5	0.30
11	3.4	5	5.0	0.26
12	3.6	5.25	5.1	0.28
13	3.8	5.25	5.3	0.22
14	4.0	5.25	5.7	0.12
15	4.2	5.25	5.5	0.15
16	4.4	5.5	6.0	0.12

Note: The slump was reported to the nearest 0.25 inch based on ASTM C143.

The SAM test results are shown in Figure 4-9.

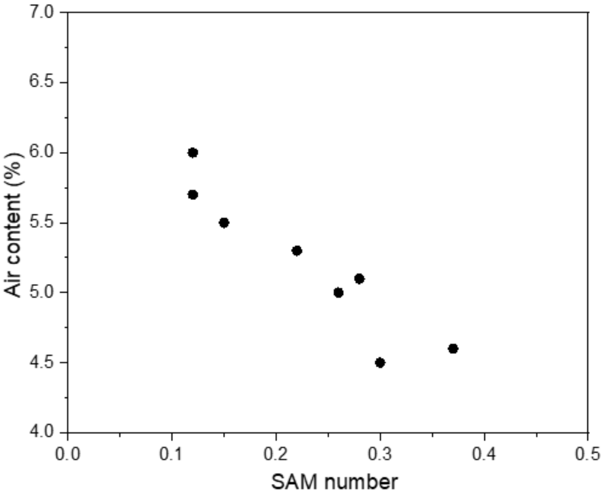


Figure 4-9. SAM test results of fresh Class A concrete (Region 1)

The test results of hardened concrete, such as 28-day compressive strength, air void parameters, and freeze-thaw durability factor (DF), are summarized in Table 4-9 and Table 4-10.

TABLE 4-9. Compressive strength, air void parameters, and DF of Class D concrete (Region 1)

Number	ASTM C39 test	ASTM C457 test			ASTM C666 test
	Compressive strength (PSI)	Air content (%)	Spacing factor (mm)	Specific Surface (mm^{-1})	Durability Factor (%)
1	6413	5.0	0.284	16.9	88.30
2	6328	5.5	0.276	16.6	N/A
3	6192	6.1	0.228	19.2	N/A
4	6205	5.8	0.125	35.9	N/A
5	6139	6.4	0.159	26.5	N/A
6	6499	4.4	0.264	19.3	N/A
7	6442	5.2	0.094	50.1	N/A
8	6647	5.7	0.335	13.5	72.85

TABLE 4-10. Compressive strength and air void parameters of Class A concrete (Region 1)

Number	ASTM C39 test	ASTM C457 test		
	Compressive strength (PSI)	Air content (%)	Spacing factor (mm)	Specific Surface (mm^{-1})
9	5183	4.2	0.416	12.3
10	5192	4.3	0.265	19.1
11	5068	5.2	0.292	15.9
12	5071	5.6	0.217	20.6
13	4952	6.1	0.274	15.6
14	5020	5.4	0.168	27.1
15	4924	6.2	0.112	37.4
16	4859	5.8	0.091	48.4

4.2.2 Test results of lab concrete mixes made using raw materials from Region 2

The mix design data of Class A concrete provided by the qualified concrete plant in Region 2 are shown in Table 4-11.

TABLE 4-11. Mix design data of the Class A concrete (Region 2)

CLASS of CONCRETE	Class A lb/yd^3
CEMENT (TYPE I)	485
FLY ASH	125
GGBFS	0
CRUSH STONE #57	1830
MANUFACTURED SAND	0
NATURAL SAND	1225
WATER	242
AEA (Isosphere 5004)	6 oz
HRWR (Isoflow 7730)	17 oz
DESIGN W/CM RATIO	0.40
DESIGN AIR CONTENT	6%

During the research duration of the study, number 1 to 8 in Table 4-12 were produced. For these samples, the dosage of AEA was adjusted to change the air void system, but other variables/conditions were kept the same. The number 1 is the same as the mix design provided by the concrete plant, and the 2nd to the 8th were changed by the dosage of AEA. The resultant slump, air content, and SAM number was tested as per ASTM C143 and AASHTO TP118, as summarized in Table 4-12.

TABLE 4-12. Slump and SAM test results of fresh Class A concrete (Region 2)

Number	Variables (AEA dosage, oz/yd^3)	Test results		
		Slump (inch)	Air content (%)	SAM number
1	6.0	1	4.7	0.32
2	6.2	1	4.8	0.35
3	6.4	1	5.0	0.26
4	6.6	1	5.3	0.29
5	6.8	1	5.5	0.24
6	7.0	1	5.7	0.27
7	7.2	1	5.9	0.13
8	7.4	1	6.3	0.16

Note: The slump was reported to the nearest 0.25 inch based on ASTM C143.

The SAM test results are shown in Figure 4-10.

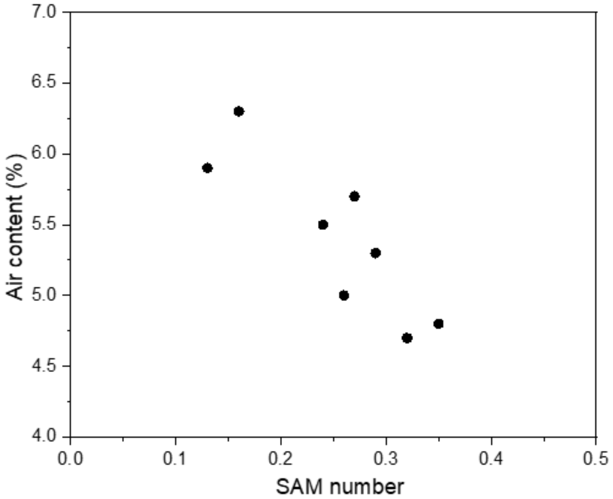


Figure 4-10. SAM test results of fresh Class A concrete (Region 2)

The mix design data of Class D concrete provided by the qualified concrete plant in Region 2 are shown in Table 4-13.

TABLE 4-13. Mix design data of the Class D concrete (Region 2)

CLASS of CONCRETE	Class D lb/yd^3
CEMENT (TYPE I)	530
FLY ASH (Class F)	113
GGBFS	0
SILICA FUME	0
CRUSH STONE #57	1800
MANUFACTURED SAND	0
NATURAL SAND	1175
WATER	250
AEA (Isosphere 5004)	3.5 oz
REDUCER (Isoflow 7730)	32.2 oz
DESIGN W/CM RATIO	0.39
DESIGN AIR CONTENT	7%

During the research duration of the study, number 9 to 16 in Table 4-14 were produced. For these mixes, the dosage of AEA was gradually adjusted (increased or decreased) to change the air void system, but other variables/conditions were kept the same.

The number 9 is the same as the mix design provided by the concrete plant, and the 10th to the 16th were changed by the dosage of AEA. Immediately after mixing, the resultant slump, air content, and SAM number were tested as per ASTM C143 and AASHTO TP118, as summarized in Table 4-14. The reported results are the average of two tests.

TABLE 4-14. Slump and SAM test results of fresh Class D concrete (Region 2)

Number	Variables (AEA dosage, oz/yd^3)	Test results		
		Slump (inch)	Air content (%)	SAM number
9	3.5	6	5.8	0.23
10	3.7	6	6.0	0.25
11	3.9	6	6.1	0.18
12	4.1	6	6.4	0.09
13	4.3	6.25	6.9	0.14
14	3.3	6	5.5	0.17
15	3.1	6	5.4	0.17
16	3.0	5.75	5.1	0.35

Note: The slump was reported to the nearest 0.25 inch based on ASTM C143.

The SAM test results are shown in Figure 4-11.

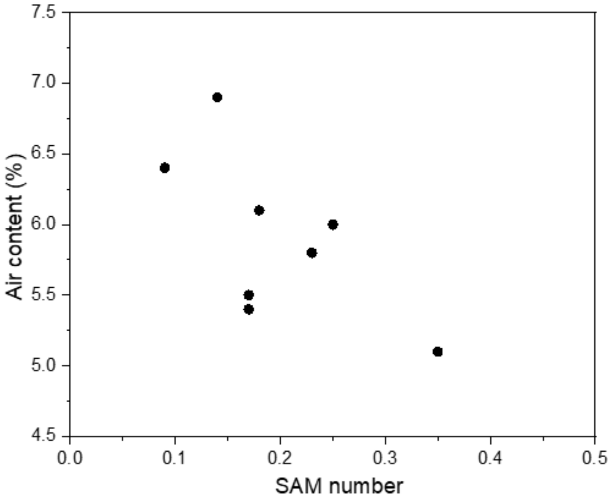


Figure 4-11. SAM test results of fresh Class D concrete (Region 2)

The test results of hardened concrete, such as 28-day compressive strength, air void parameters, and freeze-thaw durability factor (DF), are summarized in Table 4-15 and Table 4-16.

TABLE 4-15. Compressive strength, air void parameters, and DF of Class A concrete (Region 2)

Number	ASTM C39 test	ASTM C457 test			ASTM C666 test
	Compressive strength (PSI)	Air Content (%)	Spacing factor (mm)	Specific Surface (mm^{-1})	Durability Factor (%)
1	5362	4.3	0.261	19.4	75.27
2	5409	4.9	0.396	12.0	64.39
3	5214	4.7	0.158	30.7	78.83
4	5108	5.6	0.237	18.9	82.69
5	5196	5.0	0.179	26.3	85.99
6	5102	5.2	0.218	21.2	82.90
7	5013	6.3	0.079	52.2	91.78
8	4786	6.8	0.104	36.8	93.56

TABLE 4-16. Compressive strength, air void parameters, and DF of Class D concrete (Region 2)

Number	ASTM C39 test	ASTM C457 test			ASTM C666 test
	Compressive strength (PSI)	Air content (%)	Spacing factor (mm)	Specific Surface (mm^{-1})	Durability Factor (%)
9	5950	5.4	0.186	24.9	73.58
10	5912	6.5	0.163	25.5	N/A
11	5918	6.3	0.126	34.0	N/A
12	5742	7.0	0.081	47.6	N/A
13	5612	7.5	0.184	19.6	N/A
14	5953	6.1	0.137	32.0	N/A
15	6044	5.3	0.119	39.3	N/A
16	5973	5.7	0.425	10.6	55.36

4.2.3 Test results of lab concrete mixes made using raw materials from Region 3

The mix design data of Class A concrete provided by the qualified concrete plant in Region 3 are shown in Table 4-17.

TABLE 4-17. Mix design data of the Class A concrete (Region 3)

CLASS of CONCRETE	Class A
	lb/yd^3
CEMENT (TYPE I)	423
FLY ASH (CLASS C)	141
GGBFS	0
SILICA FUME	0
Crush stone #57	1800
MANUFACTURED SAND	0
NATURAL SAND	1245
WATER	250
MasterAir AE 200	3.7 oz
Enviromix 740	22.5 oz
DESIGN W/CM RATIO	0.44
DESIGN AIR CONTENT	6%

During the research duration of the study, number 1 to 8 in Table 4-18 were produced. For these mixes, the dosage of AEA was adjusted (increased or decreased) to change the air void system, but other variables/conditions were kept the same.

Number 1 is the same as the mix design provided by the concrete plant, and the 2nd to the 8th were changed by the dosage of AEA. Immediately after mixing, the resultant slump, air content, and SAM number was tested as per ASTM C143 and AASHTO TP118, as summarized in Table 4-18. The reported results are the average of two tests.

TABLE 4-18. Slump and SAM test results of fresh Class A concrete (Region 3)

Number	Variables (AEA dosage, oz/yd^3)	Test results		
		Slump (inch)	Air content (%)	SAM number
1	3.7	3	5.2	0.28
2	3.9	3	5.3	0.17
3	4.1	3	5.4	0.21
4	4.3	3.25	5.5	0.14
5	4.5	3.25	5.3	0.16
6	4.7	3.25	6.0	0.13
7	4.9	3.5	6.1	0.08
8	5.1	3.5	6.1	0.09

Note: The slump was reported to the nearest 0.25 inch based on ASTM C143.

The SAM test results are shown in Figure 4-12.

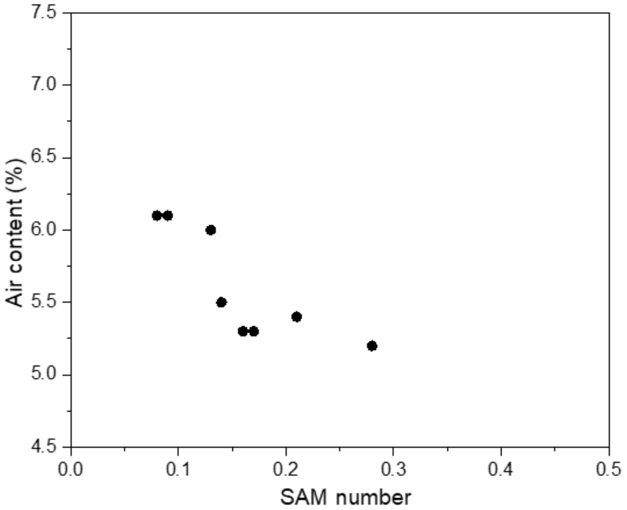


Figure 4-12. SAM test results of fresh Class A concrete (Region 3)

The mix design data of Class D concrete provided by the qualified concrete plant in Region 3 are shown in Table 4-19.

TABLE 4-19. Mix design data of the Class D concrete (Region 3)

CLASS of CONCRETE	Class D
	lb/yd^3
CEMENT (TYPE I)	465
FLY ASH (CLASS C)	155
GGBFS	0
SILICA FUME	0
Crush stone #57	1780
MANUFACTURED SAND	0
NATURAL SAND	1170
WATER	250
MasterAir AE 200	4.03 oz
Enviromix 740	35 oz
DESIGN W/CM RATIO	0.4
DESIGN AIR CONTENT	7%

During the research duration of the study, number 9 to 16 in Table 4-20 were produced. For these mixes, the dosage of AEA was adjusted (increased or decreased) to change the air void system, but other variables/conditions were kept the same.

The number 9 is the same as the mix design provided by the concrete plant, and the 10th to the 16th were changed by the dosage of AEA. Immediately after mixing, the resultant slump, air content, and SAM number was tested as per ASTM C143 and AASHTO TP118, as summarized in Table 4-20. The reported results are the average of two tests.

TABLE 4-20. Slump and SAM test results of fresh Class D concrete (Region 3)

Number	Variables (AEA dosage, oz/yd^3)	Test results		
		Slump (inch)	Air content (%)	SAM number
9	4	6	5.8	0.17
10	4.2	6	6.0	0.12
11	4.4	6	6.3	0.14
12	4.6	6.25	6.4	0.11
13	5.0	6.25	6.8	0.13
14	5.2	6.5	7.0	0.09
15	3.8	6	5.7	0.18
16	3.6	5.75	5.3	0.25

Note: The slump was reported to the nearest 0.25 inch based on ASTM C143.

The SAM test results are shown in Figure 4-13.

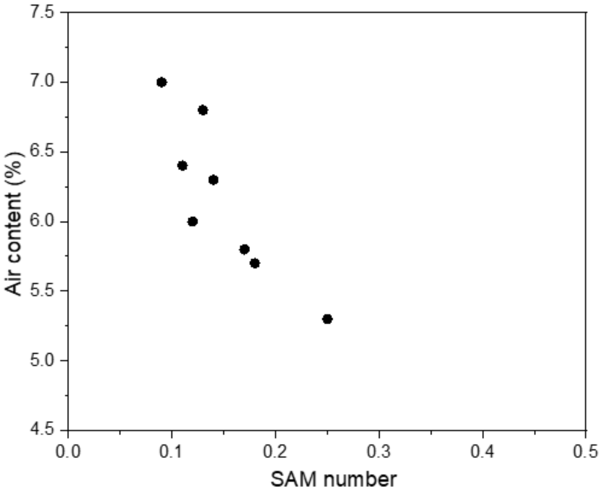


Figure 4-13. SAM test results of fresh Class D concrete (Region 3)

The test results of hardened concrete, such as 28-day compressive strength, air void parameters, and freeze-thaw durability factor (DF), are summarized in Table 4-21 and Table 4-22.

TABLE 4-21. Compressive strength and air void parameters of Class A concrete (Region 3)

Number	ASTM C39 test	ASTM C457 test		
	Compressive strength (PSI)	Air content (%)	Spacing factor (mm)	Specific Surface (mm^{-1})
1	4859	5.9	0.336	13.1
2	4846	5.7	0.253	17.6
3	4817	6.1	0.186	22.9
4	4794	6.8	0.121	31.6
5	4902	5.0	0.089	52.9
6	4671	7.8	0.165	20.2
7	4618	7.6	0.103	33.2
8	4593	8.2	0.068	46.6

TABLE 4-22. Compressive strength and air void parameters of Class D concrete (Region 3)

Number	ASTM C39 test	ASTM C457 test		
	Compressive strength (PSI)	Air content (%)	Spacing factor (mm)	Specific Surface (mm^{-1})
9	6084	5.3	0.241	19.4
10	6015	5.6	0.174	26.2
11	5872	6.2	0.082	53
12	5906	6.3	0.158	27.1
13	5747	6.7	0.113	35.7
14	5609	7.8	0.074	46.8
15	6078	5.1	0.231	20.6
16	6136	4.7	0.286	17.3

4.2.4 Test results of lab concrete mixes made using raw materials from Region 4

The mix design data of Class D concrete provided by the qualified concrete plant in Region 4 are shown in Table 4-23.

TABLE 4-23. Mix design data of the Class D concrete (Region 4)

CLASS of CONCRETE	Class D lb/yd^3
CEMENT (TYPE I)	465
FLY ASH (CLASS C)	155
GGBFS	0
SILICA FUME	0
SURF.CONCGRAVEL #57	1600
MANUFACTURED SAND	0
NATURAL SAND	1151
WATER	248
AEA (MasterAir AE 90)	6.0 oz
REDUCER (MasterPozzolith 700)	12.4 oz
HRWR (MasterGlenium 7920)	18.6 oz
DESIGN W/CM RATIO	0.40
DESIGN AIR CONTENT	7%

During the research duration of the study, number 1 to 8 in Table 4-24 were produced. For these mixes, the dosage of AEA was adjusted (increased or decreased) to change the air void system, but other variables/conditions were kept the same.

The number 1 is the same as the mix design provided by the concrete plant, and the 2nd to the 8th were changed by the dosage of AEA. Immediately after mixing, the resultant slump, air content, and SAM number was tested as per ASTM C143 and AASHTO TP118, as summarized in Table 4-24. The reported results are the average of two tests.

TABLE 4-24. Slump and SAM test results of fresh Class D concrete (Region 4)

Number	Variables (AEA dosage, oz/yd^3)	Test results		
		Slump (inch)	Air content (%)	SAM number
1	6.0	6	6.1	0.18
2	6.2	6	6.2	0.29
3	6.4	6.25	6.5	0.15
4	6.6	6.25	6.6	0.16
5	6.8	6.25	6.8	0.11
6	7.0	6.5	7.1	0.13
7	5.8	6	6.1	0.19
8	5.6	6	5.7	0.42

Note: The slump was reported to the nearest 0.25 inch based on ASTM C143.

The SAM test results are shown in Figure 4-14.

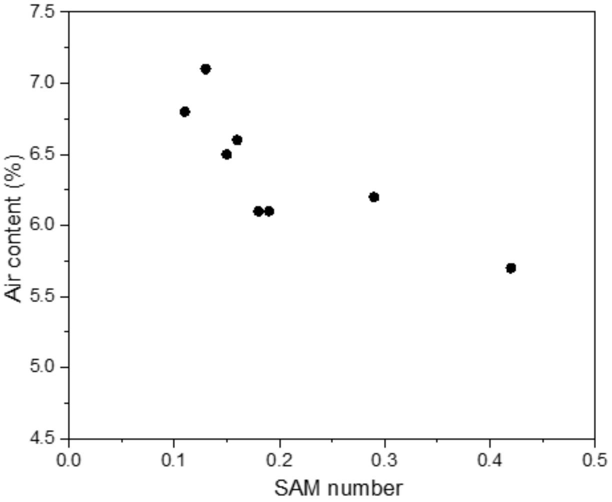


Figure 4-14. SAM test results of fresh Class D concrete (Region 4)

The mix design data of Class A concrete provided by the qualified concrete plant in Region 4 are shown in Table 4-25.

TABLE 4-25. Mix design data of the Class A concrete (Region 4)

CLASS of CONCRETE	Class A lb/yd^3
CEMENT (TYPE I)	423
FLY ASH (CLASS C)	141
GGBFS	0
SILICA FUME	0
Crush stone #57	1800
MANUFACTURED SAND	0
NATURAL SAND	1225
WATER	254
AEA (MasterAir AE 90)	6 oz
WR (MasterPozzolith 700)	17 oz
DESIGN W/CM RATIO	0.45
DESIGN AIR CONTENT	6%

During the research duration of the study, number 9 to 16 in Table 4-26 were produced. For these mixes, the dosage of AEA was adjusted (increased or decreased) to change the air void system, but other variables/conditions were kept the same.

The number 9 is the same as the mix design provided by the concrete plant, and the 10th to the 16th were changed by the dosage of AEA. Immediately after mixing, the resultant slump, air content, and SAM number was tested as per ASTM C143 and AASHTO TP118, as summarized in Table 4-26. The reported results are the average of two tests.

TABLE 4-26. Slump and SAM test results of fresh Class A concrete (Region 4)

Number	Variables (AEA dosage, oz/yd^3)	Test results		
		Slump (inch)	Air content (%)	SAM number
9	6.0	3.5	6.3	0.11
10	6.2	3.5	6.5	0.08
11	6.4	3.5	6.4	0.12
12	6.6	3.5	7.0	0.09
13	5.8	3.25	6.4	0.15
14	5.6	3.25	6.2	0.17
15	5.4	3.25	5.7	0.19
16	5.2	3.25	5.3	0.24

Note: The slump was reported to the nearest 0.25 inch based on ASTM C143.

The SAM test results are shown in Figure 4-15.

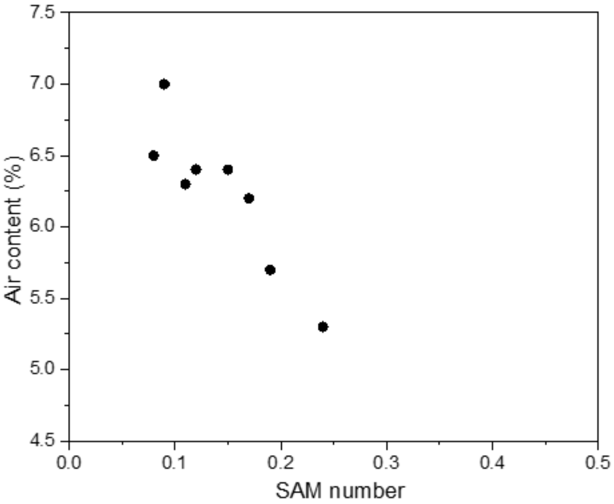


Figure 4-15. SAM test results of fresh Class A concrete (Region 4)

The test results of hardened concrete, such as 28-day compressive strength, air void parameters, and freeze-thaw durability factor (DF), are summarized in Table 4-27 and Table 4-28.

TABLE 4-27. Compressive strength, air void parameters, and DF of Class D concrete (Region 4)

Number	ASTM C39 test	ASTM C457 test			ASTM C666 test
	Compressive strength (PSI)	Air content (%)	Spacing factor (mm)	Specific Surface (mm^{-1})	Durability Factor (%)
1	5597	5.5	0.271	16.9	82.77
2	5583	5.1	0.363	13.1	N/A
3	5474	5.6	0.122	37.3	N/A
4	5379	5.9	0.086	51.7	N/A
5	5374	6.1	0.159	27.5	N/A
6	5284	8.0	0.163	20.7	N/A
7	5451	5.8	0.247	18.1	N/A
8	5592	5.1	0.338	14.1	51.25

TABLE 4-28. Compressive strength and air void parameters of Class A concrete (Region 4)

Number	ASTM C39 test	ASTM C457 test		
	Compressive strength (PSI)	Air content (%)	Spacing factor (mm)	Specific Surface (mm^{-1})
9	4973	7.2	0.169	21.4
10	4928	6.8	0.106	36.1
11	4981	6.0	0.092	47.1
12	4795	7.8	0.127	26.2
13	4827	7.1	0.138	26.5
14	5014	5.7	0.224	19.8
15	5126	5.2	0.145	31.9
16	5249	4.6	0.273	17.9

4.3 Field Testing of Fresh Concrete Mixes Using AVA

During the research duration of the study, the UTK research team contacted FHWA to acquire the Mobile Concrete Trailer (MCT), which includes the Super Air Meter (SAM) and the Air Void Analyzer (AVA), and received training.

Then UTK research team performed SAM and AVA tests on fresh concrete mixes in Region 1. The mix design is summarized in Table 4-29. Actually, this concrete was one of 14 field concrete mixes as listed in Table 4-1.

TABLE 4-29. Mix design data of Class A concrete

CLASS of CONCRETE	Class A lb/yd^3
CEMENT (TYPE I)	423
FLY ASH (CLASS F)	141
GGBFS	0
SILICA FUME	0
CRUSH STONE #57	1800
MANUFACTURED SAND	1398
NATURAL SAND	0
WATER	253
CHEMICAL ADMIXTURES	1, 2, 3, 4, 5[a]
DESIGN W/CM RATIO	0.45
DESIGN AIR CONTENT	6%

Note: 1-Air entraining admixture (MasterAir AE 90), 5-High range water reducer (MasterGlenium 7920).

The results of the SAM test on fresh concrete are shown in Figure 4-16.

(a) Air content

(b) SAM number

Figure 4-16. SAM test results of fresh Class A concrete (Region 1)

The results of the SAM test on fresh concrete are summarized in Table 4-30.

TABLE 4-30. SAM test results of fresh concrete

Test device	FHWA's		UT's	
Two test results	Air content	SAM number	Air content	SAM number
	4.1%	0.41	4.1%	0.38
Average	Air content=4.1%, SAM=0.40			

Note: The air content tested by TDOT staff using traditional Type B Pressure Meter on the construction site was 4%.

Also, based on FHWA suggestions, fresh concrete was cast in a 100×200 mm cylinder and delivered to the UTK laboratory for an AVA test. The construction site is very close to the UTK campus (about 6-min driving), and the specimens were held in hand carefully to avoid vibration.

The AVA test was conducted on a mortar sample from the fresh concrete of 100×200 mm cylinder. The mortar sample (excluding aggregate larger than 6 mm) was extracted using a 20-ml syringe and then injected into the bottom of the AVA test device, a temperature-conditioned riser column assembly that contains a layer of viscous, blue liquid under a column of water. The sample was gently stirred for 30 seconds. Air bubbles were released from the mortar and rise through the viscous liquid and then through the water in the rising cylinder. Based on Stoke's Law, the rate air bubbles rise at is a function of their size—larger bubbles rise faster than smaller ones.

The AVA test is shown in Figure 4-17. Because the AVA test equipment is very sensitive to vibration, the operator should avoid touching it during the test.

Figure 4-17. AVA test of fresh Class A concrete (Region 1)

The results of the AVA test on fresh concrete are summarized in Table 4-31.

TABLE 4-31. AVA test results of fresh concrete

Test device	FHWA's		
Test results	Air content (%)	Spacing factor (mm)	Specific surface (mm^{-1})
	2.3	0.405	17.7

Note: Because the AVA test equipment only counts air bubbles less than 2 mm, the measured air content was lower than that measured by the pressure method (traditional Type B Pressure Meter or Super Air Meter). Based on the literature, the AVA method usually results in about 2% lower air content than other methods.

The ASTM C457 and ASTM C666 test results of hardened concrete are summarized in Table 4-32.

TABLE 4-32. ASTM C457 and ASTM C666 test results of hardened concrete

Test methods	ASTM C457 test			ASTM C666 test
Test results	Air content (%)	Spacing factor (mm)	Specific surface (mm^{-1})	Durability factor (%)
	3.2	0.483	11.9	39.51

4.4 Statistical Analyses

In this section, comprehensive statistical analyses were performed on the test results from 14 field concrete mixes and 66 lab concrete mixes. Among these 80 concrete mixes, two of them were non-air-entrained (one was from the field; the other was from the lab), while 78 of them were air-entrained.

Figure 4-18 shows the air content of fresh concrete mixes versus the freeze-thaw durability factor (DF) of hardened concrete. Two non-air-entrained concrete mixes had air content below 3%, and their DF were below 60%, indicating poor freeze-thaw resistance. It was also observed that 3 air-entrained concrete mixes with an air content of 4%~6% had DF lower than 60%. Although their air contents met the requirements of TDOT specification, their freeze-thaw durability could not meet the ASTM C666 or AASHTO T161 failure limit of 60%. In addition, the DF of 7 air-entrained concrete mixes with an air content of 4%~6% were between 60% and 80%, indicating unsatisfactory freeze-thaw resistance. The DF of the remaining 14 air-entrained concrete mixes were higher than 80%, displaying satisfactory freeze-thaw durability.

Therefore, the above test results further confirmed that using air content alone could not effectively ensure enough freeze-thaw durability of concrete mixes. This finding was consistent with the test results only from field concrete mixes, as mentioned before.

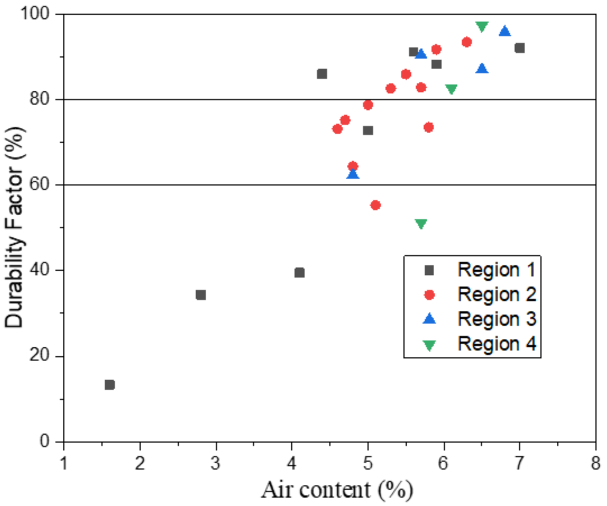


Figure 4-18. Air content of fresh concrete versus durability factor of hardened concrete

Figure 4-19 shows the air content of fresh concrete mixes versus the spacing factor of hardened concrete. A lower spacing factor is desired for good freeze-thaw durability. ACI 201 suggests that the spacing factor in concrete should be 0.2mm (0.008 in) or below for adequate freeze-thaw durability [27]. This limit is shown in Figure 4-19 with a horizontal line.

Two non-air-entrained concrete mixes had air content below 3% (1.6% and 2.8%), which were from entrapped air voids. Their spacing factor was 0.514 mm and 0.659 mm, respectively, much higher than the limit of 0.2 mm recommended by ACI 201. This was because the average distance between entrapped air voids was large without the entrained air voids. After air entrainment (e.g., 4%~8% for Class A, 4.5%~7.5% for Class D), the spacing factor decreased. However, the spacing factor showed relatively large differences. Among 78 air-entrained concrete mixes, 13% or 10 of them had spacing factor higher than 0.3 mm, 27% or 21 of them had spacing factor between 0.2 mm and 0.3 mm, 60% or 47 of had spacing factor below 0.2 mm.

Although the air content of fresh air-entrained concrete mixes complied with TDOT specification, their spacing factor varied widely. This indicates the inadequacy of using air content alone to predict the high quality of the air void system and thus enough freeze-thaw resistance of concrete.

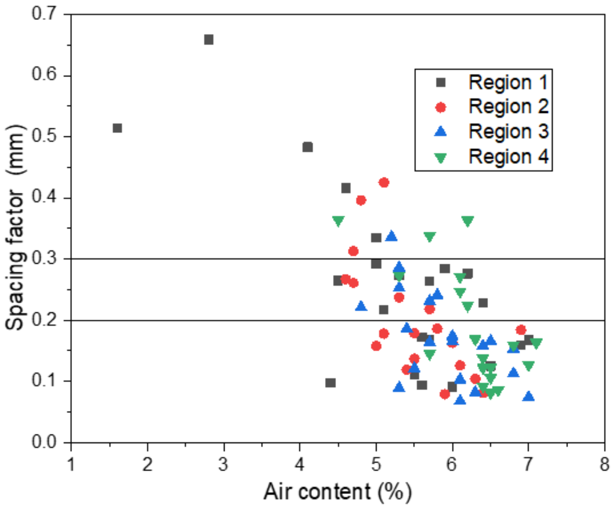


Figure 4-19. Air content of fresh concrete versus a spacing factor of hardened concrete

Figure 4-20 shows the air content of fresh concrete versus the SAM number of fresh concrete. It is obvious that the SAM number varied widely, indicating there is no good consistency of a SAM number for TDOT concrete mixes. The variation of the SAM number showed the difference in the air void system of fresh concrete mixes. It is clear that the SAM number presents a decreasing trend with the increase of air content. When the air content was lower than 3%, the SAM number was higher than 0.4. When the air content was between 4% and 5%, the SAM number of most concrete mixes was higher than 0.3. When the air content was higher than 5%, the SAM number of most concrete mixes was lower than 0.3. When the air content was higher than 6%, the SAM number of most concrete mixes was lower than 0.2. A lower SAM number indicates a better air void system of fresh concrete [12, 16, 28]. Therefore, the increase of air content resulted in the decrease of SAM number, producing a higher quality of air void system in fresh concrete. In practice, the increase of air content can be achieved by increasing air-entraining admixture (AEA) dosage. In other words, if it is found that SAM number is relatively high, increasing AEA dosage can reduce it to acquire a better quality of air void system.

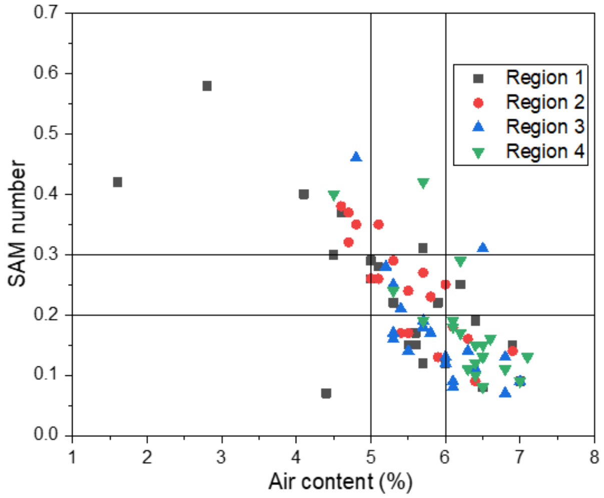


Figure 4-20. SAM number versus air content of fresh concrete

Figure 4-21 shows the air content of fresh concrete versus the air content of hardened concrete. It was found that compared with fresh concrete, the air content was higher or lower in hardened concrete. There is no equal relationship between the air content of fresh concrete and hardened concrete [49-50]. This discrepancy could be caused by many factors such as air voids stability in plastic concrete, placement, and consolidation [39]. Furthermore, this discrepancy can also increase due to the various test methods for taking a measurement of air content in fresh and hardened concrete [51].

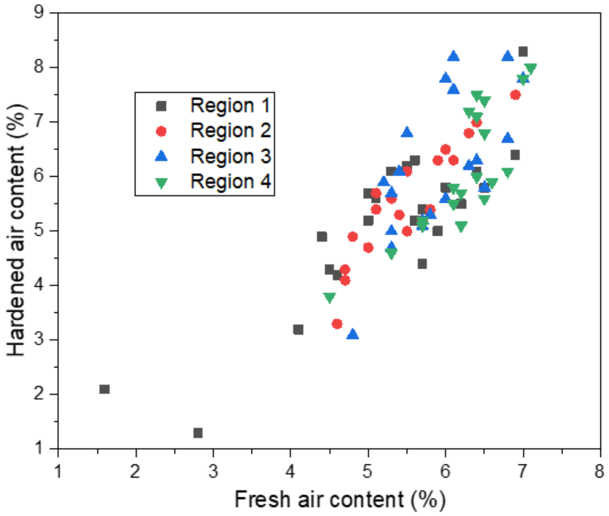


Figure 4-21. Air content of fresh concrete versus air content of hardened concrete

Figure 4-22 shows the spacing factor of hardened concrete versus the freeze-thaw durability factor (DF) of hardened concrete. Overall, the DF showed a decreasing trend with the increase of spacing factor. The spacing factor indicates the average distance between air voids in concrete. A higher spacing factor means that water/ice would have to travel longer distances to get into air voids to alleviate the hydraulic and osmotic pressures induced by the expansion of water under the freezing conditions, and thus concrete is more susceptible to freeze-thaw damage. Currently, the spacing factor is the most commonly used air void parameter to evaluate the freeze-thaw durability of concrete. ACI 201 suggests that the spacing factor in concrete should be 0.008in (0.2mm) or below for freeze-thaw durability. This limit is shown in Figure 4-22 with a horizontal line. It was observed that most concrete mixes with spacing factor lower than 0.2 mm had DF higher than 80%, showing satisfactory freeze-thaw resistance. Seven concrete mixes had a spacing factor between 0.2 mm and 0.3 mm; 4 of them had DF higher than 80%, which indicated enough freeze-thaw resistance. Seven concrete mixes had spacing factor higher than 0.3 mm; 2 of them had DF between 60% and 80%, which showed unsatisfactory freeze-thaw resistance, and 5 of them had DF lower than 60%, which showed poor freeze-thaw resistance.

It is worth mentioning that the spacing factor of 0.2 mm recommended by ACI 201 is a conservative upper limit. Some researchers reported that some concrete mixes with a spacing factor higher than 0.2 mm still had adequate freeze-thaw resistance [52-53]. In this study, most concrete mixes with a spacing factor between 0.2 mm and 0.3 mm also had good DF. Therefore, the spacing factor of 0.3 mm can also be used as a second upper limit.

A spacing factor of 0.2 mm was plotted in Figure 4-22 with a vertical line, while a DF of 80% was plotted in Figure 4-22 with a horizontal line. It is clear that the data in Figure 4-22 were separated into four quadrants. The spacing factor correlated/agreed well with DF in the upper left quadrant and lower right quadrant: the upper left quadrant indicates satisfactory freeze-thaw resistance, while the lower right quadrant indicates unsatisfactory freeze-thaw resistance. The spacing factor did not correlate/agree well with DF in the lower left quadrant and upper right quadrant. Among these 26 concrete mixes, 20 or 77% of them showed a good correlation between the spacing factor of 0.2 mm and DF of 80%. Similarly, among these 26 concrete mixes, 21 or 81% of them showed a good correlation between the spacing factor of 0.3 mm and DF of 80%. Therefore, the spacing factor of 0.2 mm or 0.3 mm showed an adequately accurate level to evaluate the freeze-thaw resistance of hardened concrete in Tennessee. However, although the ASTM C457 air void parameter test takes much less time than the ASTM C666 freeze-thaw test, it is still conducted on hardened concrete, which is not suitable for QC/QA purposes in the field.

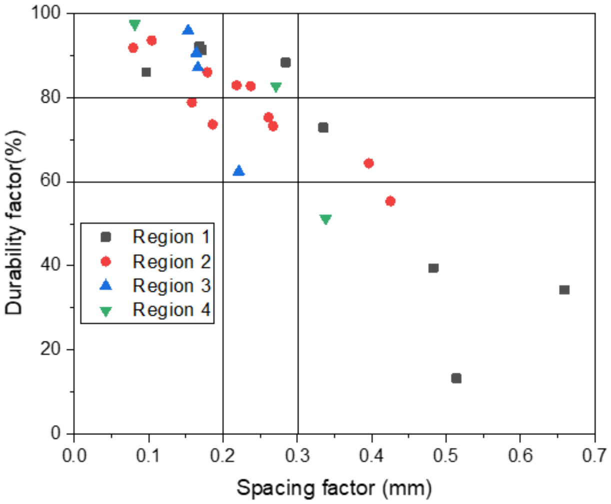


Figure 4-22. Spacing factor versus durability factor of hardened concrete

Figure 4-23 shows the SAM number of fresh concrete versus the DF of hardened concrete. Overall, the DF showed a decreasing trend with the increase of SAM number. A high SAM number indicates a poor quality of air void system in concrete, which is detrimental to the freeze-thaw resistance. The concrete mixes with SAM number below 0.2 had DF higher than 80%, indicating satisfactory freeze-thaw resistance. Seven concrete mixes had SAM number between 0.2 and 0.3, 4 of them had DF higher than 80%, which indicated good freeze-thaw resistance. When the SAM number is higher than 0.3, most concrete mixes had DF lower than 80% and even lower than 60%, showing unsatisfactory or poor freeze-thaw resistance. Therefore, it is appropriate to use the SAM number to predict the DF of TDOT concrete mixes. From a conservative perspective, 0.2 can be used as the threshold value of the SAM number. In addition, it is also feasible to use 0.3 as the upper limit of SAM number for TDOT concrete mixes.

A SAM number of 0.2 was plotted in Figure 4-23 with a vertical line, while a DF of 80% was plotted in Figure 4-23 with a horizontal line. It is clear that the data in Figure 4-23 were separated into four quadrants. The SAM number correlated well with DF in the upper left quadrant and lower right quadrant: the upper left quadrant indicates satisfactory freeze-thaw resistance, while the lower right quadrant indicates unsatisfactory freeze-thaw resistance. The SAM number did not agree well with DF in the lower left quadrant and upper right quadrant. Among these 26 concrete mixes, 21 or 81% of them showed a good correlation between SAM number of 0.2 and DF of 80%. Similarly, among these 26 concrete mixes, 22 or 85% of them showed a good correlation between SAM number of 0.3 and DF of 80%. Although the agreement was not 100%, it still showed an adequately accurate level. Therefore, it is proper to use the SAM number to predict the DF of hardened concrete in Tennessee.

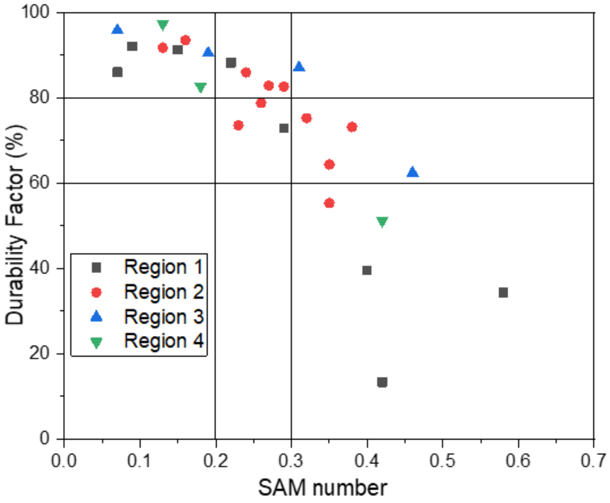


Figure 4-23. SAM number versus durability factor of hardened concrete

Figure 4-24 shows the SAM number of fresh concrete versus the spacing factor of hardened concrete. Overall, the spacing factor showed an increasing trend with the increase of SAM number. Since a spacing factor of 0.2 mm is recommended by ACI 201, this threshold is shown in Figure 4-24 with a horizontal line. As mentioned before, a SAM number of 0.2 correlated well with satisfactory freeze-thaw durability in this study, as shown in Figure 4-24. In addition, a SAM number of 0.2 has also been used or recommended by other DOTs from the survey results.

Therefore, the target value of 0.2 was used as the threshold of SAM number, as plotted in Figure 4-24 with a vertical line. It is clear that the data in Figure 4-24 were separated into four quadrants. The SAM number correlated well with the spacing factor in the lower left quadrant and upper right quadrant: the lower left quadrant indicates satisfactory air void systems, while the upper right quadrant indicates unsatisfactory air void systems. The SAM number did not agree well with the spacing factor in the upper left quadrant and lower right quadrant.

Among these 80 concrete mixes, 66 or 83% of them showed a good correlation between a SAM number of 0.2 and spacing factor of 0.2 mm. Similarly, among these 80 concrete mixes, 71 or 89% of them showed a good correlation between SAM number of 0.3 and spacing factor of 0.3 mm, as shown in Figure 4-24. Although the agreement was not 100%, it still showed an adequately accurate level. Therefore, it is proper to use the SAM number to predict the spacing factor of hardened concrete in Tennessee.

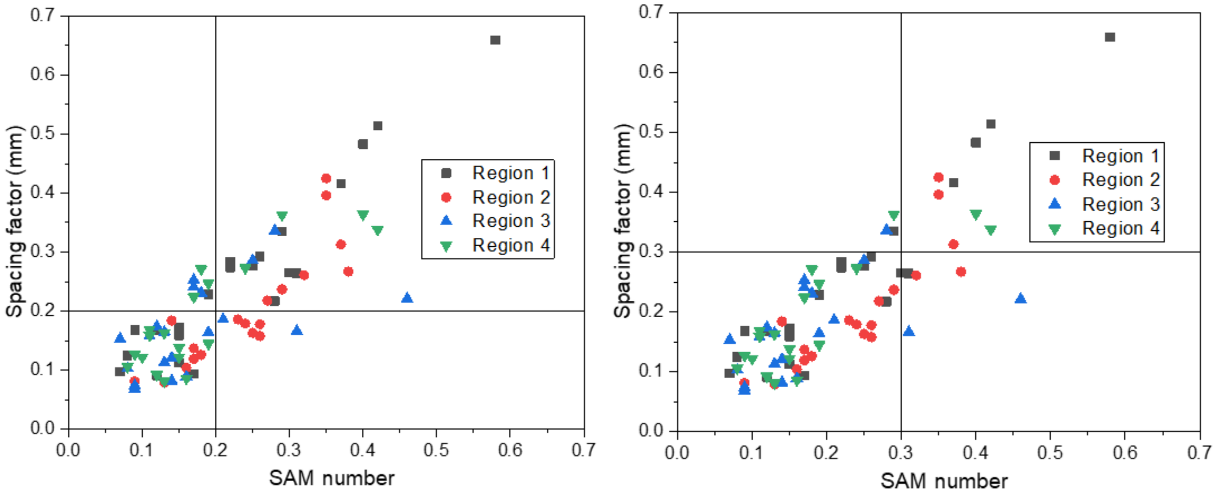


Figure 4-24. SAM number versus spacing factor of hardened concrete

Chapter 5 Conclusions and Recommendations

This study aims to investigate the applicability of SAM to TDOT concrete mixes and the suitability of SAM number as a QC/QA tool for freeze-thaw resistance and to determine the acceptance criterion for the SAM number if it can be adopted for QC/QA purposes. To achieve this goal, the research team first conducted a synthesis of literature review on the latest advances in the SAM test method and SAM number and surveyed state DOTs on their acceptance criteria of a SAM number for adequate freeze-thaw resistance of concrete. Then, various concrete mixes across Tennessee on the job sites and in the laboratory were tested for their SAM numbers, as well as other air void parameters (e.g., total air content, spacing factor, and specific surface), and the freeze-thaw durability factor from ASTM C666/AASHTO T161. Third, a statistical analysis on the consistency of the SAM number values and correlations of the SAM number to other air-void parameters as well as to the freeze-thaw durability factor were performed. Based on the field and lab test results and analyses, it is found that the SAM test is applicable for TDOT concrete mixes, and the SAM number is suitable as a QC/QA tool for freeze-thaw resistance, and the acceptance criterion for the SAM number was determined.

5.1 Conclusions

The key conclusions are summarized below.

1. For TDOT concrete mixes, only the fresh air content requirements (e.g., 4%~8% for Class A, 4.5%~7.5% for Class D) does not necessarily guarantee high quality of air void system and enough freeze-thaw resistance.
2. For TDOT concrete mixes in different regions, the measured SAM number varies widely, indicating there is no good consistency of a SAM number in various locations. The variation of the SAM number actually reflected the difference in the air void system of fresh concrete mixes.
3. For TDOT concrete mixes, the SAM number shows a decreasing trend with the increase of air content of fresh concrete.
4. For TDOT concrete mixes, there is a good correlation between the SAM number and freeze-thaw durability factor:
    - A SAM number of 0.2 shows a correlation to a durability factor of 80% with 81% agreement.
    - A SAM number of 0.3 shows a correlation to a durability factor of 80% with 85% agreement.
5. For TDOT concrete mixes, there is a good correlation between the SAM number and spacing factor:
    - A SAM number of 0.2 shows a correlation to a spacing factor of 0.2 mm with 83% agreement.
    - A SAM number of 0.3 shows a correlation to a spacing factor of 0.3 mm with 89% agreement.

5.2 Recommendations

The key recommendations are summarized below.

1. SAM is applicable to TDOT concrete mixes to evaluate the air void system and freeze-thaw resistance, and a SAM number can be adopted as a QC/QA tool. Not only the air content for fresh concrete should meet TDOT specification (e.g., 4%~8% for Class A, 4.5%~7.5% for Class D), but also an appropriate SAM number is recommended. The following acceptance criteria of a SAM number for TDOT concrete mixes can be adopted.
    - From a conservative perspective, a SAM number below 0.2 can be considered as good enough to ensure concrete has sufficient freeze-thaw durability factor (e.g., higher than 80%).
    - A SAM number between 0.2 and 0.3 can be considered as acceptable to ensure concrete has a freeze-thaw durability factor meeting the failure limit (e.g., higher than 60%).
    - A SAM number above 0.3 can be considered as rejectable. To remedy such fresh concrete mixes, the most straightforward method is to increase the air content (e.g., adding more air entraining admixture), then SAM number will decrease to a proper value for acceptance.

This study shows that SAM is useful for TDOT concrete mixes based on statistical analyses from field and lab test results. The expected benefits include but are not limited to the improvement in the freeze-thaw durability of concrete with less or no cracking, the extended service life of concrete structures, significant cost savings to TDOT due to reduced maintenance and rehabilitation activities.

Future research may focus on the mechanism behind SAM number to better understand the air void system of concrete.

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Appendices

A. Responses to DOTs survey

A total of 30 states responded to the DOTs survey, and 31 responses were received during the research duration of the study, as listed in Table A-1.

TABLE A-1 Responses to DOTs survey

No.	State Responded	No. of Respondents	No.	State Responded	No. of Respondents
1	Iowa	1	16	North Carolina	1
2	Texas	1	17	Alabama	1
3	Rhode Island	1	18	Georgia	1
4	Indiana	1	19	New York	1
5	Oklahoma	1	20	Illinois	1
6	South Carolina	1	21	Ohio	1
7	Washington	1	22	Louisiana	1
8	Wisconsin	1	23	Delaware	2
9	Kansas	1	24	Maryland	1
10	Virginia	1	25	Montana	1
11	Colorado	1	26	New Jersey	1
12	Utah	1	27	Minnesota	1
13	North Dakota	1	28	Pennsylvania	1
14	Mississippi	1	29	Alaska	1
15	California	1	30	Kentucky	1

The responses to the DOTs survey were analyzed, and the results are summarized as follows. It should be noted that the responses to some questions are not available (N/A).

The University of Tennessee

Enhancing Freeze-Thaw Resistance of Tennessee Concrete Mixes through Improved Air Void Testing

Super Air Meter (SAM) is a modified ASTM C231 Type B pressure meter gauge with a digital pressure gauge and six restraining clamps, which can assess the air void system of fresh concrete mixes based on the total air content and SAM number parameters it provides. SAM number was found to correlate well to the spacing factor and freeze-thaw resistance (e.g., the durability factor) of concrete. This questionnaire is prepared by the University of Tennessee, with the aim to find ways to identify best practices for freeze-thaw resistance of concrete and make recommendations for state specifications and operational guidelines regarding the applicability of SAM to concrete mixes and the consistency of the SAM number. Your response to this questionnaire will be beneficial to this study and is highly appreciated.

Note: The answers to some of the following questions can be multiple choices.

1. At present, what parameters are used as QC/QA tools to characterize the freeze-thaw resistance of concrete mixes in your state?
a. Total air content
b. Spacing factor
c. Specific surface
d. Freeze-thaw durability factor (ASTM C666)
e. SAM number
f. Other parameters (please list below)

____

Among the 30 responded states, a total of 17 states currently only uses total air content as QC/QA tools to characterize the freeze-thaw resistance of concrete mixes. A total of 11 states currently uses total air content and spacing factor/specific surface (ASTM C457) and/or freeze-thaw durability factor (ASTM C666) as QC/QA tools to characterize the freeze-thaw resistance of concrete mixes. North Dakota state uses total air content and SAM number as QC/QA tools. Alaska state uses total air content, SAM number, and w/c (water/cementitious materials) ratio as QC/QA tools. Kansas State is about to implement the SAM soon. New York state has pilots that are using SAM for QA, but it's only on a handful of jobs and not statewide at this point.

2. If the answers to Q1 include Freeze-thaw durability factor (ASTM C666), what is the failure criteria for the durability factor of hardened concrete in your state?
a. < 60%
b. < 70%
c. < 80%
d. Other criteria (please list below)

____

4 states (Rhode Island, Illinois, Delaware, Kentucky) currently use durability factor < 80% as the failure criteria. Oklahoma state currently uses durability factor < 50% as the failure criteria. Maryland state currently uses durability factor < 60% as the failure criteria. Washington state currently uses durability factor < 90% as the failure criteria for bridge decks. Kansas state currently uses ASTM C666 Procedure B to conduct the freeze-thaw test and regard durability factor <95% after 660 cycles as the the failure criteria.

3. At present, what parameters are used to characterize the air-void system of hardened concrete in your state?
a. Total air content
b. Spacing factor
c. Specific surface
d. Other parameters (please list below)

____

18 states currently only use total air content to characterize the air-void system of hardened concrete. 4 states (Texas, Kansas, Illinois, Delaware) currently use total air content and spacing factor and/or specific surface (ASTM C457) to characterize the air-void system of hardened concrete. Ohio state currently does not check hardened air after placement but will perform spacing factor and specific surface as part of a petrographic analysis if issues arise. Montana state does not specify ASTM C457 to characterize the air-void system of hardened concrete but may use ASTM C457 to verify air content for investigation. Minnesota state currently requires ASTM C457 for trial batching for HPC bridge decks, but does not have any specifications limits tied to it.

4. At present, what types of tests are used to determine the air void system of fresh concrete mixes in your state?
a. Pressure air meter test (ASTM C231)
b. Gravimetric method (ASTM C138)
c. Volumetric Method (ASTM C173)
d. Super Air Meter
e. Air Void Analyzer (AVA)
f. Other methods (please list below)

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14 states currently only use Pressure air meter test (ASTM C231 or AASHTO T152) to determine the air void system of fresh concrete. Georgia state currently only uses GDT 26 equipment which is similar to ASTM C231/TypeB to determine the air void system of fresh concrete. 9 states currently use Pressure air meter test (ASTM C231) and Volumetric Method (ASTM C173) to determine the air void system of fresh concrete. Delaware state currently uses Pressure air meter test (ASTM C231) and Air Void Analyzer (AVA) to determine the air void system of fresh concrete. North Dakota state and Alaska state currently use Pressure air meter test (ASTM C231) and Super Air Meter (SAM) to determine the air void system of fresh concrete. CO Colorado state currently uses Super Air Meter (SAM) to determine the air void system of fresh concrete. Kansas state currently uses Pressure air meter test (ASTM C231), Gravimetric method (ASTM C138), Volumetric Method (ASTM C173), Air Void Analyzer (AVA), and Super Air Meter (SAM) to determine the air void system of fresh concrete. New York state currently uses Pressure air meter test (ASTM C231), Volumetric Method (ASTM C173), and Super Air Meter (SAM) to determine the air void system of fresh concrete, but SAM testing is part of a Performance Engineered Mix Pilot program and not a current standard.

5. If the answer to Q1/Q4 is not SAM, is there any correlations between other air-void parameters of fresh/hardened concrete (e.g., total air content, the spacing factor and specific surface) and freeze-thaw resistance (e.g., the freeze-thaw durability factor)? If Yes, please describe below.

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For Iowa state, total air is used for acceptance, Spacing factor is monitored to watch for trends.

For Rhode Island state, they have SAM equipment, but haven't implemented its use in regular practice. Historically, they have some comparison of total air to ASTM C666/C215 testing. They would like to develop a correlation between SAM and the durability factor.

For Oklahoma state, they are looking at the SAM but have moved forward yet due to cost.

For SC state, they're not aware of any correlations in their state. They specify 3 to 6 percent air for all concrete that would be susceptible to any freeze thaw damage.

For Kansas state, there are correlations between other air-void parameters of fresh/hardened concrete and freeze-thaw resistance based on previous studies.

For California state, 6% +/-1.5% is sufficient for freeze-thaw environments.

For Alabama state, freeze-thaw isn't a significant concern for them.

For Illinois state, they generally follow typical recommendations for entrained air: 5 - 8%; that along with pre-qualifying coarse aggregates for D-cracking resistance and air-entraining admixtures per ASTM C260 appears to be largely satisfactory. Hardened air analysis is only performed for forensic needs, and parameters are based on ACI's recommendations.

6. If the answer to Q1/Q4 is SAM, what is the threshold of SAM number with adequate freeze-thaw resistance for concrete mixes?

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Kansas state currently uses the threshold of SAM number: SAM number <0.2 = good, SAM number <0.3 = ok, SAM number=0.3-0.4 = bad, SAM number >0.4 = no good. North Carolina state is not currently using SAM number, but research has shown that NC's SAM number would be 0.30 based on current mixes. New York state currently uses target SAM number less than 0.2 during mix design, and wants SAM number under 0.3 in the field, and SAM number above 0.35 is reject-able. Ohio state has done some minor research, and 0.30 to 0.35 seemed to give good durability, but has not evaluated the decks where used and it has been a couple years. Minnesota state has played with 0.25 in the pilot projects with anything over 0.30 as make cylinders for hardened air content testing for information only. Oklahoma state is working to establish these values currently. Wisconsin state is currently collecting SAM data to determine an appropriate SAM number for specification implementation. North Dakota state has not established and is collecting the SAM data for future spec implementation. Alaska state currently uses 0.2 as the threshold of SAM number.

7. If the answer to Q1/Q4 is SAM, is the SAM number applicable and consistent to various concrete mixes in your state?

a. Yes b. No

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For Kansas state, SAM number applicable and consistent to various concrete mixes.

8.If the answer to Q1/Q4 is SAM, is there any correlations between SAM number and freeze-thaw resistance (e.g., the durability factor) in your state? If Yes, please describe below.

For Kansas state, there is correlations between SAM number and freeze-thaw resistance based on previous studies. For Colorado state, there are some correlations between SAM number and freeze-thaw resistance. For North Dakota state, typically SAM number of mixes are 0.30 or lower and have good freeze thaw performance over time.

9. If the answer to Q1/Q4 is SAM, is there any correlations between SAM number and other air-void parameters of fresh/hardened concrete (e.g., total air content, the spacing factor and specific surface) ? If Yes, please describe below.

For Kansas state, there are correlations between SAM number and other air-void parameters of fresh/hardened concrete; SAM includes spacing factor an specific surface in it's measurement.

For New York state, if the total air content is on the higher side (8%+) the SAM number will be good. For Illinois state, limited field testing so far does not indicate a strong correlation between SAM number and hardened air parameters; that is, they have found that the hardened air parameters are usually satisfactory despite the SAM number being greater than 0.20-0.25.

10. If the answer to Q1/Q4 is SAM, (1) do you currently use SAM as a QC/QA tool in your state? (2) In addition, is SAM used for Acceptance testing or Verification testing? (3) What is the frequency required to be run for the SAM tests? (4) What types of concrete are being tested with the SAM?

For Kansas state, they are about to use SAM as a QC/QA tool; SAM used for both Acceptance testing and Verification testing; The frequency required to be run for the SAM tests is 1 SAM /200 CY; Everything except mixes with LW aggregates are being tested with the SAM.

For North Dakota state, SAM is used during the mix design process, but they are looking to rolling it out as a QC/QA tool in the future; SAM used for for mix design Verification; The frequency required to be run for the SAM tests is one per mix design, if moved to the field it would be 1 test per 2,000 SY of concrete pavement; All mainline paving mixes during mix design verification are being tested with the SAM.

For New York state, they have a pilot performance mix program working to incorporate SAM into our acceptance procedures; Currently it is not an acceptance tool; In the pilot program, the SAM test is done once every production day, or at least once every 200 yards; In the pilot program, all concrete on a project is designed using SAM.

For Illinois state, SAM is currently being trialed at the Districts' discretion to gain familiarity with the equipment and procedure.

For Minnesota state, SAM is not used as a QC/QA tool at this point; On the pilot project they have done a frequency of SAM (1 out of every 4 contractor QC tests or 1 every 1200 cy).

For Alaska state, they are trying SAM with 9000 psi prestressed bridge girders with much difficulty so far.

11. If the answer to Q1/Q4 is SAM, is there any lessons from past failed cases in your state?

For New York state, they found that if the SAM number is low during mix design (0.15-0.2), then they get good SAM numbers (less than 0.3) in the field.

For Illinois state, the 'touchy' nature of the SAM procedure (e.g., cleaning the rim) has been problematic in the fast-paced construction environment they often experience; for example, when trying to match the frequency of our typical C231 air testing, testing for SAM number became harried and thus possibly prone to user error.

For Alaska state, HRWR anti-foam agent consumes air. taking out the small bubbles first.

For Kansas state, Trained Operators are key. Functioning Machines are key.

For Minnesota state, the biggest impact MnDOT has had with the SAM is to eliminate testing before and after the paver to measure the air content due to air loss from vibration. They determined they were losing primarily entrapped not entrained air and decided not to test after the paver and put a hole in the concrete. Secondly, they are embarking soon on doing some MnDOT specific testing pre and post pump with the intentions of eliminating testing after the pump for general concrete pumped mixes. They are more apprehensive about heavy admxitured and SCC type mixes and will take our time with that.

B. A brief introduction to the linear traverse method

The calculation principle of air void parameters is the linear traverse method (LTM) [11], briefly introduced as follows.

LTM requires that a series of equally spaced straight lines be traversed across the surface of the concrete specimen, as shown in Figure A-1.

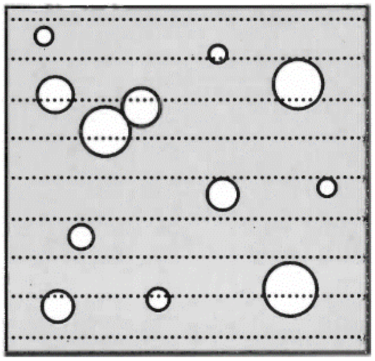

Figure A-1. Linear traverse method [39]

As these lines are traversed, the total length traversed (T_t), the length traversed through air voids (T_a), and the total number of air voids intersected by the traverse lines (N) are tallied. Then the air void parameters can be calculated as follows:

Air content (A), in %:

$$A=\frac{T_a}{T_t}\times 100\P$$

Specific surface (α), in mm^{-1}:

$$\alpha=\frac{4N}{T_a}\P$$

Spacing factor ($\bar{L}$), in mm:

$$\bar{L}=\frac{P}{\alpha A}\text{, if }\frac{P}{A}\leq 4.342\P$$

$$\bar{L}=\frac{3}{\alpha}\left[1.4\left(1+\frac{p}{A}\right)^{\frac{1}{3}}-1\right]\text{, if }\frac{P}{A}>4.342$$

Where $\frac{P}{A}$ is the paste to air ratio, and P is the paste content (volume fraction, %), which can be computed from the mix design data:

$$P=\frac{m_c}{S_c}+\frac{m_{SCMs}}{S_{SCMs}}+\frac{m_w}{S_w}$$

Where,

m_c-mass of cement

S_c -specific gravity of cement

m_{SCMs}-mass of supplementary cementitious materials (SCMs)
S_{SCMs}-specific gravity of supplementary cementitious materials (SCMs)
m_w-mass of water
S_w-specific gravity of water

It is worth noting that the volume of chemical admixtures is negligible due to their too little dosage in the concrete mix design, so it is not included in the above equation.
For field specimen 1, based on the mix design data, P can be calculated as follows:
m_c= 800 lbs/yd^3=474.621 kg/m^3
S_c= 3.15 g/cm^3=3150 kg/m^3
m_{SCMs}=0,
m_w= 295 lbs/yd$^{3=}$ 175.017 kg/m^3
S_w=1 g/cm^3=1000 kg/m^3

$$P=\frac{m_c}{S_c}+\frac{m_{SCMs}}{S_{SCMs}}+\frac{m_w}{S_w}=\frac{474.621}{3150}+0+\frac{175.017}{1000}=0.326\approx 0.33=33\%$$