

A Road Map for Research and Implementation of Freeze-Thaw Resistant Highway Concrete

Tara L. Cavalline, M. Tyler Ley, Lawrence L. Sutter, W. Jason Weiss, Thomas J. Van Dam

Abstract

The freeze thaw (F-T) durability of portland cement concrete (PCC) is a function of the exposure condition, concrete saturation, and the quality of the paste, aggregate, and air-void system. Unfortunately, the interplay of these variables is not well characterized. Because of this, most current specifications use a “one size fits all” approach to designing and specifying F-T durability, an approach that does not address the performance of modern materials, construction methods, and local exposure conditions. In some cases this leads to overdesign of concrete that wastes money and resources. In other cases key performance criteria may be missed that shortens the service life of a highway structure, such as a pavement, bridge element, etc. This paper outlines a *road map* for research and implementation leading to highway concrete design and specification for F-T durability. The proposed implementation is to consider the local exposure, design life, allowable risk, available materials, construction practices, and maintenance procedures as inputs to the design of the project. This decision making process will help design engineers address the critical F-T variables and provide a robust approach to obtaining F-T durability that can be tailored to the needs of the project. *All details of this approach are not provided as they are still being established through ongoing or proposed research.* Instead, this paper establishes the need, outlines the framework for this approach, and initiates the discussion of what critical details are needed and how they might be obtained.

Introduction

For nearly 100 years, the importance of producing a properly air entrained hydrated portland cement paste has been known to be a key contributor to the durability of portland cement concrete (PCC) in wet, freeze-thaw (F-T) environments. Methods for characterizing the air-void system in concrete and evaluating concrete F-T performance have been utilized for decades. However, results from these tests have not always correlated well with field performance. Further, a number of other factors including more complex combinations of concrete-making materials, accelerated construction, and use of alternative deicers have led, on occasion, to failures to achieve an air-void system that is adequate for the exposure conditions.

Despite possessing the knowledge needed to construct durable concrete, failures from F-T still persist. In order to provide stakeholders the tools necessary to produce F-T durable highway concrete, a decision-making framework, or Guide, to the design and construction of F-T durable concrete is needed. This Guide must combine the best practices from published literature with newly established test methods to create a proven process to ensure the durability of concrete structures (note that “structures” refers to pavements, bridges, and other concrete highway elements including retaining walls, barriers, etc.) in a number of exposure conditions. Application of the Guide will result in the procurement and placement of concrete that is F-T durable, contributing to long-lasting concrete highway infrastructure.

The research that will be required to develop this Guide must also investigate and establish the validity of a number of advancements in material design and testing for air-void system characteristics in fresh and hardened concrete, and for evaluating F-T resistance. A wealth of knowledge has been produced in previous years in areas related to F-T durability. Additionally, a number of recent advancements in understanding the characteristics of F-T durable concrete, as well as test methods utilized for QA/QC have been made. Research required to complete the Guide can build upon recent advancements in these key areas, performing laboratory and field work that will develop the precision and bias of existing tests and identify/develop new or modified test methods for measuring air-void system characteristics and concrete F-T durability. This paper establishes the need for the Guide, provides a framework for the Guide as envisioned by the authors, identifies the research needed to prepare the Guide, and methods to improve the

Guide after it is put forth and utilized by practitioners. In summary, this is a roadmap to improvement of F-T durability.

Background

Although concrete is well known for its inherent durability, there are specific areas where its durability can be improved. For highway concrete placed in wet, F-T environments, tensile stresses develop as absorbed liquid water transforms to ice (Scherer and Valenza 2005). When the water saturation of the concrete reaches a critical value, a single F-T cycle can lead to cracking (Fagerlund 1993, Litvan and Sereda 1980, Li et al. 2012). The combination of saturated concrete and F-T temperature cycling leads to a significant durability issue for concrete structures. To improve F-T durability, air is entrained in concrete to create a network of closely spaced air-voids in the hydrated cement paste. Entrained air-voids are spherical in shape and can be as small as 0.01 mm. Air entrainment is most commonly accomplished through the use of an air entraining admixture (AEA), which is added before or during concrete mixing. Air entrainment helps to reduce the degree of saturation and reduces the travel length of moisture during freezing making the concrete more resistant to damage caused by F-T (Powers 1975, Fagerlund 1972, Fagerlund 1975, Fagerlund 1977, Scherer and Valenza 2005). In addition to protecting the hardened cement paste from F-T damage, entrained air also improves the workability of fresh concrete, and can reduce segregation and bleeding (Kosmatka et al. 2011).

The properties of an air-void system needed to protect a concrete against F-T damage are well known and are characterized by a number of common measurements including the total air content, the spacing factor, and the specific surface of the air-void system (Mindess et al. 2002, Kosmatka et al. 2011). Although these characteristics are established, consistently obtaining in-place concrete with the necessary characteristics is not always assured. An AEA stabilizes air bubbles during mixing and can be sensitive to mixing action, temperature, chemistry of the cementitious materials and other admixtures, and gradation of the aggregates (Whiting and Stark 1983, Whiting and Nagi 1998, Plante et al. 1989, Saucier et al. 1990). Modern construction demands more complex combinations of concrete-making materials and accelerated construction, presenting new challenges with respect to producing durable concrete structures.

Tests to evaluate PCC for its durability in a F-T environment have been used for decades and include AASHTO T 161 (ASTM C666) “*Standard Method of Test for Resistance of Concrete to Rapid Freezing and Thawing*” and ASTM C672 “*Standard Test Method for Scaling Resistance of Concrete Surfaces Exposed to Deicing Chemicals*.” However, these laboratory tests often fail to adequately predict field performance of concrete mixtures (Nmai 2006). In some cases, this can be traced to the inadequacy of the test. More importantly, these tests were developed when concrete mixtures and placement techniques were less complex and may have been less demanding. Also, concrete is now placed in more severe exposure conditions with widespread use of chemical deicer combinations.

Historically, concrete has faced other durability challenges and as state highway agencies (SHAs) seek to develop solutions to F-T durability issues, it is useful to examine how these other durability issues have been approached and determine if the methodologies used in those cases could be adapted to address F-T durability issues. The most notable and recent advancement in design tools for concrete durability has occurred in the area of alkali-silica reactivity (ASR) (Thomas et al. 2012). Over the past 20-30 years, major research initiatives have been undertaken to address ASR. These include development of test methods, strategies for proper mixture design, protocols for proper construction including quality control/quality assurance (QC/QA), and field demonstrations to validate each of these individual steps. This process has recently culminated in AASHTO PP 65-11 “*Standard Practice for Determining the Reactivity of Concrete Aggregates and Selecting Appropriate Measures for Preventing Deleterious Expansion in New Concrete Construction*.” This practice summarizes the state-of-knowledge of the engineering and scientific community regarding ASR and distills that information into prescriptive and performance engineering approaches that can be used for designing concrete mixtures that are durable for a range of materials and concrete exposures. As SHAs now turn their attention to the problem of resistance to F-T distress and deterioration, it is thought by the authors that a similar approach will provide immense benefits to highway practitioners.

As is the case with ASR, over the past 20 years, research has led to a better understanding of F-T deterioration and how it can be addressed in highway concrete. With respect to the materials used, the need for a proper air-void system has been reconfirmed in countless studies, but the role of other concrete properties has also been clearly identified. These are generally placed into the categories of paste quality, aggregate quality, and pore fluid properties. Paste quality addresses issues such as cement content, use of supplementary cementitious materials (SCMs), and the mixture's water-to-cementitious ratio (w/cm). Aggregate quality can be considered to include the chemical and physical properties of the aggregates, resistance of the aggregates to freezing damage, and also the combined grading of the aggregate used (Stark 1976). Fluid properties consider the degree of saturation, surface tension, viscosity and ionic concentration (Spragg et al. 2011). Additionally, the role of variations in the air-void system that occur during the construction, placement, and finishing processes has been studied, and key factors have been identified including air loss through the paver or pump (Rupnow 2008), concrete placement temperature (Saucier et al. 1991), concrete finishing technique (Whiting and Schmitt 1987), construction equipment configuration and operating parameters. Finally, current maintenance practices have also been studied and their effects on F-T performance identified. Most notably this includes the role of deicer chemicals and deicing practices on F-T deterioration (Verbeck and Klieger 1957, Browne and Cady 1975, Sutter et al. 2006A, Sutter et al. 2006B, Li et al. 2012, Todak et al. 2015). Moving forward, material selection and highway structure design and construction must accommodate these maintenance practices, which are used to maximize the safety of the travelling public.

For an agency to design and construct concrete structures that are F-T durable, it is the opinion of the authors that it is necessary to assimilate new and existing information into a Guide that will provide SHA personnel, in a concise and readily usable format, the available information to construct F-T durable concrete highway structures. The information should be presented in both prescriptive- and performance-based terms, considering all known material, construction, and exposure factors. While much of this information already exists from previous studies, there is a need to assemble existing information in a coherent manner and there are still several areas of research needs. Some specific needs include a better understanding of F-T performance of highway concrete in the field and better test methods that can rapidly and accurately provide guidance on material F-T performance. This format for this Guide is presented schematically in Figure 1. This is a preliminary, conceptual outline to present the vision of this new approach to F-T durable highway concrete. The key points of the envisioned Guide include:

- Design of Structure: The process begins with the design of the structure, for example using an approach such as the AASHTOWare Pavement ME Design software. The proposed Guide is not duplicative of this design process, but instead once the design is complete and the required concrete properties identified, the Guide will lead an engineer through the process of designing the concrete mixture to be F-T durable.
- Establish Exposure Class: The Guide will account for the exposure of the structure as well as specifics of the structure (e.g., is the concrete being designed for use as a pavement, bridge deck or parapet wall, etc.).
- Risk Classification: The Guide should also establish risk tolerance for the structure. Not every project or component on a project is expected to require the highest protection against F-T damage.
- Approach: The guidance on material selection will allow for a choice of a prescriptive approach or a performance-based approach.
- Materials and Mixture Design Selection Process: Once materials are selected for durability, the required mixture is designed and tested for durability using a protocol of testing outlined in the Guide.
- Construction Guidance: Information on construction best practices will be provided. While starting with a sound design is important, the execution of this design is equally important.
- Quality Control/Quality Assurance: QC/QA procedures will also be recommended as part of the Guide.

The envisioned Guide will provide values for specification limits for parameters required to predict F-T durability. Additionally, guidance will be provided in several key areas regarding testing to ensure

concrete with high quality aggregate, air and paste are produced and placed. These tests will involve a combination of existing tests and newly developed tests. As an illustration, Table 1 presents a summary of the conceptual approach for guidance on the three key concrete properties affecting F-T durability. The important point to note is the guidance provided should be a combination of existing methods, such as standard test methods, and new knowledge, such as test methods under development by several members of the research community.

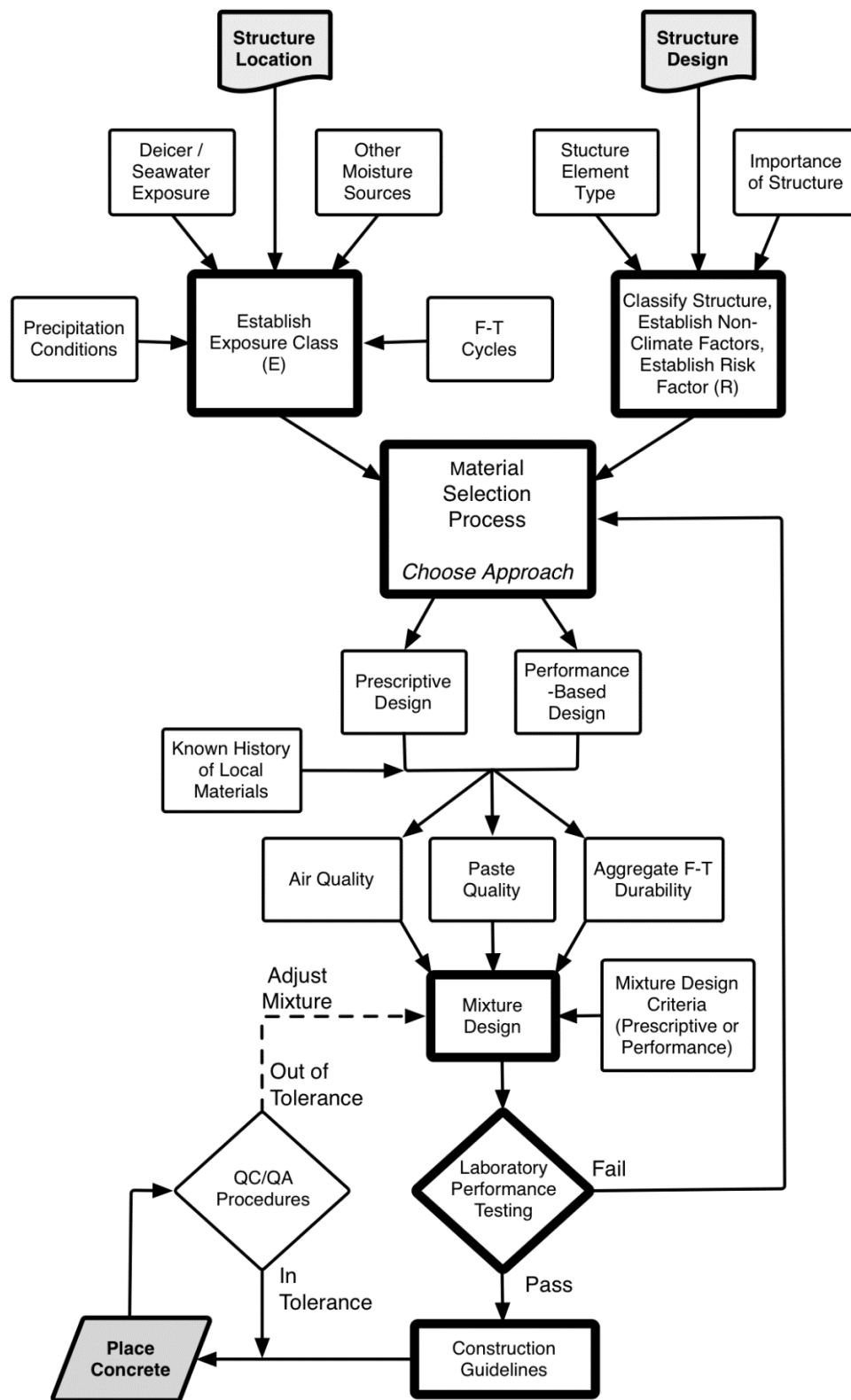


Figure 1. Conceptual framework of a Guideline for Design of Concrete for F-T Durability.

Table 1. Summary of concrete properties affecting F-T durability and example guidance to be provided for each.

Guidance	Concrete Property		
	Air Quality	Paste Quality	Aggregate Quality
Required Level of Property for F-T Durability	<i>Based on SHA experience, information from the literature, LTPP and exposure site data</i>	<i>Based on SHA experience, information from the literature, LTPP and exposure site data</i>	<i>Based on SHA experience, information from the literature, and local material histories</i>
Method of Measuring Property	<i>SAM Meter, Existing Methods (with some modifications)</i>	<i>Degree of Saturation Fluid Sorption Formation Factor</i>	<i>Iowa Pore Index Hydraulic Fracture</i>
Method of Confirming F-T Performance	<i>ASTM C457 Automated Methods</i>	<i>Low Temperature Differential Scanning Calorimeter Longitudinal Guarded Comparative Calorimeter AASHTO T 161</i>	<i>Low Temperature Differential Scanning Calorimeter Longitudinal Guarded Comparative Calorimeter AASHTO T 161</i>

Overview of the Envisioned Guidance Document

In the following sections of this paper, discussion on the envisioned approach to assimilation of known and unknown information, and subsequent development of each of the key components of the Guide, as shown in Figure 1, are presented.

Assimilation of Existing Information. To develop the Guide, effort must be made to identify the characteristics of the entrained air-void system required for F-T durability. Extensive research has been performed in this area, and sufficient information should be available through a combination of a literature review, a survey of SHAs, review of data from long-term exposure sites, and review of LTPP data. The literature review should be performed to obtain information on current practices, published research findings, and ongoing studies related to characterization of the air-void system of concrete, tests to measure F-T durability, and the understanding of the air-void system's role in the durability of concrete in highway structures.

To supplement the findings of a literature review, additional information could be obtained by conducting a survey of SHA engineers and contractors. This survey should i) identify gaps in knowledge and specifications, perceived issues with tests and specifications, or other hurdles for SHA personnel and contractors with respect to designing and constructing F-T durable highway structures, ii) summarize the range of specifications currently used in the states to achieve F-T durability, iii) establish in general the level of problems with respect to F-T durability of highway structures and identify the categories of problems that occur (e.g., transverse joint deterioration, longitudinal joint deterioration, D-cracking, scaling, etc.). By soliciting information from both SHAs and contractors, a more complete picture can be obtained about the challenges of designing and constructing F-T durable structures.

Establishing Exposure Class. As illustrated in Figure 1, taking into account the type of structure (e.g., pavement, bridge, barrier, etc.), it is necessary to understand the exposure of a structure to determine the required characteristics of concrete for F-T durability. This will be the initial step in the proposed Guide. Currently, there is no standard methodology for establishing local environmental exposure of a project in the United States. The exposure is more than simply the number of temperature cycles. It is a combination of temperature, moisture, and exposure to deicers that has, to date, not been adequately described. A complex combination of absorption and drying processes lead to a state of saturation for the concrete and as saturation increases then so does the chance for damage from freezing. Providing a SHA engineer with

the ability to uniformly assess the exposure conditions would by itself provide a step change in the industry's ability to construct F-T durable structures. It is proposed that a measure of exposure be developed that will represent the “*effective F-T cycles*” experienced by the structure. Currently, there are very few useful recommendations in the literature on this subject.

To address this in the guide document, a methodology is needed that will result in an expert system to classify areas for different effective F-T cycles for the United States needs to be developed. Development could begin by examining, for a given location, where a combination of moisture and subsequent freezing events occur on a similar temporal basis (e.g., freezing occurring within a prescribed time relative to precipitation). The specific time period would need to be analyzed and established but the point would be to identify when the concrete is exposed to moisture and in a similar time frame a F-T cycle occurs. It will also be necessary to integrate deicer application into the model as deicing and anti-icing practices will lead to melting ice or snow and thereby create a source of water. Overall, it is necessary to identify times when the concrete would be moist and then subsequently exposed to F-T cycles. Work would also need to be done to investigate the volume of moisture versus the evaporation rate to estimate how much moisture entered the concrete versus how much potentially evaporated.

These effective F-T cycles should not be obtained by simply combining precipitation and F-T maps. An expert system, which combines various data inputs and provides the results to a user using a graphical interface (e.g., Google map) should be produced to supplement the Guide. To do this, it would be necessary to specifically examine a freezing event and establish the magnitude and duration of the previous moisture event to assess the impact on the saturation of the concrete. The rate of freezing of the concrete is also important and should be examined (Pigeon et al. 1985). All required weather data is available from the National Oceanic and Atmospheric Administration (NOAA) or from local weather stations. Local deicing and anti-icing practices will need to be provided by the user. Extensive analysis of the data will be necessary, which is a significant research endeavor. Once complete, this will be a starting point for the proposed Guide procedure.

Risk Classification. Establishing a protocol for assigning risk will be more difficult and as of this writing no clear guidance exists. As one example CEB-FIP uses a very simple approach featuring four different risk categories based on the usage, needed lifespan, and importance of the structure. It is envisioned that a life cycle cost analysis (LCCA) will be the ultimate solution where the owner considers the cradle-to-grave cost of a structure. An immediate solution could be a prescriptive risk approach as was done for AASHTO PP 65-11. As LCCA models are developed through other research, they can be incorporated into the Guide as a performance alternative to the prescriptive risk model.

Materials and Mixture Design Selection Process. When seeking to maximize the F-T durability of concrete, it is common to focus almost exclusively on the air-void system as the principal factor to be controlled. But arguably, the most critical step in designing a F-T durable concrete structure is selecting proper materials and material combinations, including the air-void system (Taylor et al. 2013). This must be done with knowledge of the exposure conditions and must also consider the structure type and the level of risk the owner can tolerate with a given structure. Unfortunately, a concrete engineer does not have the luxury of designing solely to maximize F-T durability. Consideration must be given to the required concrete properties (e.g., strength, workability) but simultaneously attention must be given to other types of materials-related distress (MRD) such as ASR or sulfate attack. Additionally, cost cannot be ignored and increasingly sustainability must be considered, often leading to limitations on the available material sources to be considered. In short, the design process requires trade-offs and complex decisions. The envisioned Guide will provide needed assistance in the area of material selection for F-T durability and provide the user with a systematic approach to this otherwise complicated process. Broadly, the materials considerations can be considered in three groups: air quality, paste quality, and aggregate quality. Considerations for each are discussed briefly, below.

Air Quality. Undoubtedly, the single most important factor affecting F-T performance is the quality of the air-void system, which encompasses the volume, size, and spacing of the air-voids (Powers 1949, Powers 1975). Methods to optimize the air-void system, along with tests and specifications to assure F-T performance are of utmost importance for the Guide. The air-void system parameters typically used to evaluate the quality of an air-void system include the air content (volume %), spacing factor (in. or mm), and specific surface (in.^{-1} or mm^{-1}). These are determined in hardened concrete in accordance with ASTM C457 “*Standard Test Method for Microscopical Determination of Parameters of the Air-Void System in Hardened Concrete.*” Of these parameters the spacing factor is currently considered the primary measurement of air-void system quality. The current ASTM C457 method requires a microscope and a skilled petrographer to perform the analysis making the test difficult to apply on a routine basis. To make the test method more accessible, an automated method for performing ASTM C457 using a common flatbed scanner has been developed (Carlson et al. 2006, Sutter et al. 2007, Peterson et al. 2009).

To date, there is no accepted test method to measure the air-void system parameters in fresh concrete. Because of this, the concrete industry has measured the total volume of air in concrete with the assumption that a properly spaced air-void system will result if a minimum air content is achieved. Inherent in this assumption is that the total volume of air, which includes the entrained air-voids plus entrapped air-voids, is an accurate measure of the air content. While this may have been the case when AEAs were primarily vinsol resin-based, it can no longer be guaranteed (Felice et al. 2014). The common methods for measuring total air volume, are AASHTO T 152 (ASTM C231) “*Test for Air Content of Freshly Mixed Concrete by the Pressure Method,*” AASHTO 196 (ASTM C173) “*Standard Method of Test for Air Content of Freshly Mixed Concrete by the Volumetric Method,*” and AASHTO 121 (ASTM C138) “*Standard Method of Test for Density (Unit Weight), Yield, and Air Content (Gravimetric) of Concrete.*” Techniques for measurement of the air-void system parameters of fresh concrete include the Air Void Analyzer (AVA), and more recently, the Super Air Meter (SAM). Although some studies have shown the AVA can provide reasonable measurements of relatively small air-voids, ($D \leq 300\mu\text{m}$) (Rupnow et al. 2008), the AVA has received criticism from many state agencies for a variety of reasons, including the length of time required to perform the test, the vibration-free environment required, and the cost of the unit, among others (Desai et al. 2007). Given the shortcomings of the AVA, recent research has led to the development of a new testing device, the SAM, that is able to measure the quality of the air-void system in fresh concrete. The device and sample preparation have many similarities to the AASHTO T 152 (ASTM C231) pressure meter but the SAM test method uses higher pressures and a larger number of pressure events to determine the volume, and quality of the void distribution within fresh concrete (Ley and Tabb 2014, Welch 2014). The SAM test is outlined in AASHTO TP 118-15 “*Standard Method of Test for Characterization of the Air-Void System of Freshly Mixed Concrete by the Sequential Pressure Method*”. This test takes less than 10 minutes to run and the meter provides both the air content as determined by AASHTO T 152 (ASTM C231) and a new measurement called the SAM number that correlates F-T performance as well as or better than the spacing factor.

The Guide must incorporate recent developments of new test methods and specifications. It will also, need to make improvements to existing test methods. In general, the various tests discussed here have not been adequately compared to each other and in some cases, accurate precision statements do not exist. For example, AASHTO T 152 (ASTM C231) does not provide a precision statement for the Type B meter, the most common meter used. ASTM C457 provides a precision statement developed using a very small number of concrete samples with an unknown AEA. Without an accurate precision statement, using either method as part of a QA/QC approach is problematic. Additionally, most air tests do not adequately address calibration and therefore obtaining accurate absolute values for air contents or other parameters is not possible. As part of these efforts, existing test methods for air-void system parameters should be fully examined and the relative accuracy and precision of each should be established.

Paste Quality. The inter-relationship between the cement paste and the air-void system are most critical to durability of the hardened cement paste. The research used to establish the current air content requirements in the American Concrete Institute Committee 201 (ACI 201) Guide to Durable Concrete (2008) was

predominantly conducted prior to 1970. Since that time many changes have occurred that significantly affect the quality/characteristics of cement paste as well as the entrained air-void system. Some changes that directly impact the quality of paste include the use of lower w/cm , cements with a finer particle size, the use of paving mixtures with lower cementitious material content, and the extensive use of SCMs such as fly ash, slag cement, and silica fume.

A major difficulty in predicting the effects to concrete from changes in the paste quality is that factors contributing are diverse and not understood. It is known, for instance, that lowering the w/cm will reduce capillary porosity, therefore increasing strength and reducing the permeability of a given concrete. But how paste quality is affected by changes in cement fineness and/or chemistry, or the presence of various SCMs, is not fully understood. It may not be practical to attempt characterizing factors such as these as part of any applied guideline. Rather, it is proposed that bulk measures of cement paste quality be made for the purposes of predicting F-T durability. The principal bulk measurement could be permeability, which is commonly assessed indirectly using the rapid chloride permeability test, AASHTO T277 (ASTM C1202), *“Electrical Indication of Concrete’s Ability to Resist Chloride Ion Penetration.” Standard Specifications for Transportation Materials and Methods of Sampling and Testing,*” but is being supplanted by measurements of electrical resistivity or Formation Factor (Rajabipour 2006, Spragg et al. 2012, Weiss et al. 2015). Sorptivity also is measured, in part, as an indication of paste quality. The paste quality can also be assessed as part of the measurement of F-T performance as a function of the degree of saturation, and recent developments in this area should be incorporated into the Guide (Fagerlund et al 2004, Barde et al., 2009, Li et al. 2012, Todak et al. 2015) as should other tests that specifically focus on the resistance of paste to the diffusion of chloride ions as a measure of paste quality.

Aggregate Freeze-Thaw Durability. On a volume basis, concrete consists of 60% to 75% aggregate. Therefore, the F-T performance of the aggregates, by themselves, can dictate F-T durability of the mixture and therefore aggregate quality cannot be ignored when establishing an overall approach to producing F-T durable concrete. The use of non-durable aggregates has plagued many states in the past, so much so they have developed detailed testing protocols in order to evaluate the F-T durability of aggregates. The most common manifestation of aggregate F-T durability issues in pavements is commonly called D-cracking. Early research on the susceptibility of aggregates to D-cracking focused on mercury intrusion porosimetry, with a goal of identifying the role of an aggregate pore-size distribution on its F-T durability. These tests indicated that pores of a certain size seem to be problematic (Stark 1976).

A number of state agencies rely on different techniques to evaluate their aggregates. The practices of these states have been recently reviewed (NCC 2014) and it is reported that states routinely evaluate their aggregates by taking samples and placing them in well air-entrained concrete and evaluating their performance in rapid F-T testing. These tests are sometimes modified versions of current AASHTO T 161 methods. Other research led to the adoption by various SHAs of AASHTO T161 (ASTM C666), *“Standard Test Method for Resistance of Concrete to Rapid Freezing and Thawing.”* Some testing is also done on the aggregates themselves, including the AASHTO T 103 aggregate soundness test, Iowa Pore Index, and the hydraulic fracture test. It is apparent that states are well focused on evaluating and testing their aggregates for F-T durability. Many states seem to have found local practices that work well for them. For the Guide, it is recommended that best practices used by states be synthesized and recommendations be included for consideration by stakeholders.

Laboratory Performance Testing. Although AASHTO T 161 (ASTM C666) is the most widely used test method to evaluate F-T performance of concrete, the test has many shortcomings. Before samples are tested they are required to be stored in saturated limewater for 14 days. This means the samples never have a chance to dry before being exposed to the freezing environment. While this is a conservative approach, it is likely only representative of samples that are constantly kept moist. This also means that concretes with different paste quality will perform differently. Samples with a lower w/cm may take longer to reach a critical point of saturation (Weiss 2015). Historically, the length and weight change of the concrete was used to monitor F-T performance over 300 to 350 cycles with measurements taken every 30 cycles. More

recently, it has become common to use the change in the fundamental frequency of the specimen, which is more sensitive to the internal damage of the concrete. The square of the ratio of the fundamental frequencies before and after testing is used to calculate a term called the durability factor (DF). However, for all of these methods, there is no established failure limit for weight loss, length change, or DF. Failure criteria for DF ranging between 60 and 95 are found in specifications. This range is simply too wide and as part of developing the proposed Guide, specification limits for the DF must be addressed. Another complaint about AASHTO T 161 (ASTM C666) is that samples are only subjected to water during freezing. While it is known the presence of salts alters the freezing behavior, little research on frost damage is performed on air entrained concrete in salt water other than scaling studies. Further, it is clear that CaCl_2 and MgCl_2 exposure results in different damage mechanisms than NaCl (Sutter et al. 2008, Sutter et al. 2013, Farnam et al. 2013, Villani et al. 2015).

Utilizing existing and new test methods for measuring these characteristics will also be critical in development of the Guide, and information from ongoing research to refine existing tests, as well as to develop new tests for measuring mixture characteristics, should be assessed for incorporation. Currently, research is being performed by a number of agencies to better define the damage mechanisms of F-T, and the conditions that affect these mechanisms. For example, use of X-ray tomography to study frost damage is leading to a better understanding of the movement of water during freezing and the damage mechanisms of ice formation (Khatibmasjedi 2014). This work serves as a theoretical underpinning for new applied tests. Two tests are the focus of ongoing research to determine the sorption properties and the critical level of saturation. The sorption test is based on ASTM C1585 *Measurement of Rate of Absorption of Water by Hydraulic-Cement Concretes*, with some modifications (Bentz et al. 2012, Castro et al. 2010, Li et al. 2012). The other test is the Longitudinal Guarded Comparative Calorimeter (LGCC) (Farnam et al. 2013, Todak et al. 2015). Using these tests, mixtures susceptibility to F-T damage can be estimated in a more rapid fashion than can be accomplished with procedures such as AASHTO T 161. A low temperature differential scanning calorimeter (LT-DSC) can be used to investigate phase transformations and to detect interactions of salts with the cement paste. The LT-DSC measures the temperatures and heat flows associated with phase transitions and reactions in materials as a function of temperature. This technique provides quantitative and qualitative information about physical and chemical changes that involve endothermic or exothermic processes (Farnam et al. 2015, Monical et al. 2015).

Ultimately, the Guide will provide a means to assemble these various tests in one document, describing how and when the tests should be applied, discussing the information the test can provide, providing guidance on specification limits for each test, and providing an estimate of precision and bias for each test.

Construction Guidelines. This work supporting the road map will also create guidelines for constructing concrete highway structures. A range of construction practices should be investigated, and include plant operations, transport, placement, consolidation, finishing, and curing of the concrete. To provide useful assistance to practitioners, the format of guidelines should walk SHA personnel through the sequence shown in Figure 1 for their decisions pertaining to F-T durability. If this can be implemented, for the first time, the designer will have the ability to determine the exposure of their project and combine this with the importance of the structure to determine what quality of air-void system, paste, and aggregate is needed. Then, protocols for testing and mixture design will be given that can be used during the design of the concrete and ultimately verified in the field during construction. This document would provide the most up to date and sophisticated guidance for F-T durability available. In addition, the document should be created with guidelines on how it can evolve over time. This will allow the recommendations to adjust as new technology or findings are made and for the document to continue to serve SHAs for generations to come.

Validation and Improvement of the Guide

To supplement the development of the Guide, as well as provide a means of validation and improvement, new data from existing exposure sites, including existing LTPP sites, the USACE Treat Island site, MnRoad, and at various universities can be evaluated and incorporated as it becomes available. Further, a

detailed experimental design for a LTPP Specific Pavement Study (SPS) should be developed. The purpose of the LTPP study would be to serve as an actual design example of the recommendations made in the Guide, providing controlled, long-term test sites to validate the methodologies developed. This would provide additional information to update and improve the Guide.

Conclusion

It is postulated that a Guide is needed to help SHAs in the design and construction of F-T durable highway concrete. This Guide should be comprehensive enough to gather information about the structures exposure and risk and provide both a prescriptive and performance based design approaches to obtain F-T durability and hence long life structures. To support creation of this Guide, existing and emerging test methods should be created or updated, including development of precision and bias statements as needed. Inclusion of guidelines to build concrete pavements with a range of construction practices should be developed, and a means for improvement of the Guide to incorporate new technologies and findings should be included. The creation of an LTPP SPS test site in conjunction with this Guide would provide a true test of the recommendations and will provide great insight for future generations. The implementation of the Guide, including establishment of new test methods, improved understanding of existing ones, and the subsequent LTPP SPS project implementing these recommendations will make a transformative change in the way that concrete is designed and specified in F-T environments.

This proposed Guide will provide the industry with a tool set to minimize concrete failures as a result of inadequate F-T durability. The authors realize that although the development and adoption of this new approach will take some time, this paper has provided a comprehensive vision and outline the road map for these important changes. While new ideas will be added, a clear path forward has been presented. Development and implementation of the Guide will create tremendous savings for the public, and result in the much needed extension of our increasingly limited transportation dollars. As authors, we are committed to develop these ideas and move them into practice and look for the support of SHAs, contractors, and other researchers to work with us to make this proposed road map towards F-T durable highway concrete a reality.

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