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Determining the air-void distribution in fresh concrete with the Sequential Air Method

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HIGHLIGHTS

- A test to measure the size and spacing of air voids in fresh concrete is presented.
- The test results correlate with both the Spacing Factor and freeze-thaw durability.
- The variance of the test is similar to the Spacing Factor and freeze-thaw durability.
- The test can be completed in the field with simple equipment in less than 10 min.

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ABSTRACT

A new approach is presented to determine the air void size and spacing in fresh air entrained concrete by measuring the change in response of the concrete to a series of sequential pressures. This information is used to calculate a parameter called the Sequential Air Method (SAM) Number. Comparisons are made to hardened air void analysis (ASTM C457) from laboratory and field tests for 303 mixtures as well as rapid freeze-thaw testing (ASTM C666) for 68 mixtures to the SAM Number with over 85% agreement. Furthermore, the SAM Number showed a higher correlation to rapid freeze-thaw testing than current recommendations for the Spacing Factor. The variability of the SAM Number is compared to other direct and indirect measurements of air void size and spacing. Finally, several applications of the method are discussed along with guidance on how to specify the method.

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1. Introduction

Concrete is widely known as the building material of choice when a long-lasting structure is desired. However, concrete can be damaged when it is 1) wet and 2) exposed to freezing temperatures [1,2]. The damage that occurs due to freezing and thawing can lead to premature deterioration, costly repairs, and the need to replace concrete infrastructure components well before they reach the end of their expected lifetimes. This problem is widely known, and there are many specifications in place designed to minimize these problems.

The most widely adopted approach to producing concrete with frost durability is to add an air-entraining admixture (AEA) while the concrete is being mixed. The AEA creates small, well-dispersed, air-filled bubbles in the fresh concrete. Current theories hypothesize that these bubbles act as pressure-relief reservoirs in the hardened concrete that allow water to move during freezing [2–4]. Because a large number of variables during batching, mixing, and placement impact how AEAs perform in concrete, in practice it can be challenging to provide a consistent air-void system in hardened concrete [5]. The concrete industry would greatly benefit from tools that would help ensure that this process is done correctly and the concrete that is produced will be freeze-thaw durable.

Current specifications for freeze-thaw durability were developed more than half a century ago. These specifications are based on the measurement of total air volume in fresh concrete [6,7]. This is typically done by comparing the actual density to the theoretical, or by measuring the response of the concrete from an increase in pressure. While this past research looked at concrete with many different characteristics, such as the total volume of air, water-to-cement (w/c) ratio, mixture proportions, and different types of aggregate, the only admixture used in the research was a Vinsol

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resin AEA, as this was the only admixture available at the time. This work determined the need for 9% ±1% volume of air in the mortar [6,7], which has since been simplified to about 6% air by volume of the concrete mixture based on an expected paste volume [8]. If these criteria were met then the mixtures were expected to show satisfactory performance in laboratory freeze-thaw testing. These decades-old recommendations are still widely used to ensure freeze-thaw durability. Because of this, current specifications require the volume of air to be measured in the concrete before it has hardened.

While the specification and measurement of the total volume of air within concrete are useful, more in-depth research has shown that the size and spacing of the air-entrained bubbles are more important. For this paper, the size and spacing of the air bubbles will be combined into a term called the ''air void system quality''. Historically, the air void system quality is defined by ''the Spacing Factor'' [4,9]. The ACI 201 technical committee has recommended that a spacing factor of 200 μm be used to provide concrete with satisfactory freeze-thaw durability [10]. The spacing factor can be determined by a hardened air void analysis or petrographic analysis completed as per ASTM C457 [11]. Unfortunately, the ASTM C457 method requires significant labor, specially trained staff and equipment, and can take between 7 to 14 days to complete. However, the biggest drawback of this testing is that it cannot be used on concrete before it has hardened. This means that several days of construction could proceed before this measurement would indicate that there was an issue. Because of these challenges, most specifications measure the total volume of air in the concrete while it is being placed and assume that the correlation between air volume and air quality suggested in the work from the 1950's is satisfactory. Despite these shortcomings, the ASTM C457 test is helpful, as it can investigate hardened concrete and it provides important insights into the freeze-thaw durability of concrete that the total volume of air cannot [9]. For this reason, it will be an important method to compare to other measurements.

Since the 1950 s there have been many changes in the makeup of modern concrete mixtures and so the original recommendations of measuring only the total volume of air within concrete have been questioned [12–17]. For example, modern concrete mixtures commonly use portland cement in combination with other types of supplementary cementitious materials; mixtures often contain between three to five chemical admixtures; cement is made with new types of grinding aids that aim to reduce production energy and provide strength increases; and finally, modern construction practices are much more complex, as machines are used that pump, consolidate, and finish our concrete. There are numerous examples of how these changes have influenced the original relationship between air volume and air quality. Specific examples include different AEAs [12,13,15], admixture combinations [14,15,17] and pumping [18–21]. There has been little progress made because tools are not readily available to help investigate these issues. Because of these substantial differences in modern mixtures from those investigated in the 1950's, it is not clear if air volume specifications are still appropriate. This highlights the need for a new tool to provide more insight into the quality of the air void system during construction so that near real-time changes can be made to ensure that concrete that is freeze-thaw durable is being used and provide useful insights into how different additives or processes impact the quality of the air void system.

Modern tools are needed to build confidence that concrete construction will be long-lasting in freeze-thaw environments while also minimizing the amount of material that is rejected at the job site. Ideally, these tools could be used during both the development of the concrete mixtures and then again at the job site to evaluate the material. In addition, the measurements should be robust, accurate, and provide answers in a timely manner that correlate to historic measurements of freeze-thaw durability. Previous techniques have tried to address this by measuring the bubbles separated from the concrete through agitation of the mixture in a solution of controlled viscosity. This process liberates bubbles from the mortar and their size distribution is determined by measuring the change in the buoyancy force on an inverted plate over time [22,23]. This technique has found mixed success but has been suggested by some to be sensitive, variable, and challenging to operate in the field [24].

This paper outlines a procedure that uses sequential pressures to determine the air void quality in fresh concrete. The method is described, and results from both laboratory and field testing are presented along with the variability of the measurement. Finally, a discussion is included over the potential use and impact of the method. The goal of this paper is to introduce and establish the validity of the technique. Other papers over the mechanism and usage over a wider number of materials are in preparation.

2. Experimental methods

2.1. Materials

All the concrete mixtures in this research used a type I cement that met the requirements of ASTM C150 [25]. Both the oxide analysis and Bogue calculations for this cement used is shown in Table 1. The aggregates used were locally available crushed limestone and natural sand used in commercial concrete. The crushed limestone had a maximum nominal aggregate size of 19 mm (3/4″). One mixture contained a blend of the coarse and intermediate aggregate as well. Both the crushed limestone and the sand met ASTM C33 specifications [26] and have proven to be freeze-thaw durable. The absorption of the crushed limestone and sand was 0.60% and 0.55% respectively. All the admixtures used are described in Table 2 and met the requirements of ASTM C260 and ASTM C494 [27,28].

The wood rosin (WROS) and synthetic (SYNTH) AEA are two popular commercial AEAs. Sixteen different mixture designs were investigated and are shown in Table 3. A subset of mixtures was investigated with either a polycarboxylate (PC) superplasticizer meeting ASTM C1017 or a midrange water reducer (WR) meeting ASTM C494 [27,29]. A dose of between 60 and 200 mL/100 kg was used to increase the slump of the mixture between 50 mm to 150 mm. Between five and fourteen dosages of AEA were investigated for each mixture to achieve a range of air contents from 2% to 10%. An ASTM C618 Class C fly ash [30] was used in several of the mixtures with a 20% cement replacement by weight.

Testing was also completed with 62 field mixtures from seven different sites in Oklahoma. The majority of these samples were taken from paving projects and more details can be found in other publications [31]. Data is also included in this paper from a study completed by the US Federal Highway Administration (FHWA) Turner Fairbanks Research Lab in McLean, Virgina, USA. This allowed an independent evaluation of the method with other materials but similar methods. This work is summarized in other publications [32].

2.2. Concrete mixture procedure and testing

Aggregates were collected from outside storage piles and brought into a temperature controlled room at 23 °C for at least 24 h before mixing. Aggregates were placed in the mixer and spun and a representative sample was taken for a moisture correction. At the time of mixing all aggregate was loaded into the mixer along with approximately two-thirds of the mixing water. This combination was mixed for three min to allow the aggregates to approach