

AIR ENTRAINMENT AND CONCRETE DURABILITY

INTRODUCTION

Hydraulic cement concrete (hereafter referred to simply as concrete) is composed of aggregates bound together by a hydrated cement paste. Concrete contains a significant amount of porosity including small gel pores (0.5 to 10 nm in size) that are an intrinsic feature of the hydration products formed when water reacts with cement, capillary pores (10 nm to 10 μm in size) that are the remnant of the original water-filled space that existed between the cementitious grains at the time of mixing, and much larger spherical air voids (0.05 to 1.25 mm in size) that were purposefully entrained in the concrete (Mindess, Young, and Darwin 2003). In addition, concrete contains irregularly shaped air voids that were entrapped during the mixing process.

The entrained air component plays a critical role in ensuring the durability of the concrete and is the focus of this Tech Brief. It provides background on the mechanisms responsible for freeze-thaw damage, discusses the importance of critical saturation, and introduces specific strategies to better establish an acceptable entrained air-void system. This Tech Brief supplements the information provided in several other FHWA Tech Briefs:

- *Ensuring Durability of Concrete Paving Mixtures – Part I: Mechanisms and Mitigation* (Van Dam 2016a).
- *Ensuring Durability of Concrete Paving Mixtures – Part II: Testing and Construction* (Van Dam 2016b).
- *Chemical Deicers and Concrete Pavements: Impacts and Mitigation* (Van Dam 2018).

BACKGROUND

As concrete freezes, ice first begins to form within the larger pores. The temperature at which this occurs depends both on the size of the pores and the chemistry of the pore solution within them. The formation of ice is expansive and results in changes in the pore solution chemistry that results in the generation of stress within the concrete (Powers 1945; Powers 1954; Powers 1955, Powers and Helmuth 1956; Marchand, Pleau, and Gagné 1995; Penttala 1998; Scherer and Valenza 2005).

It is well known that the freeze-thaw durability of concrete is influenced by the size and volume of air bubbles entrained in the concrete and its permeability (ACI 2016; Kosmatka and Wilson 2016). Combined, these factors strongly influence the rate and degree to which concrete will saturate when exposed to fluids, such as water. This is illustrated in figure 1, which shows eight stages of saturation (Weiss 2014). When a dry concrete is exposed to a fluid on one side (the left side in figure 1), as would occur in a standard sorptivity test such as ASTM C1585, the fluid is first absorbed into the smallest pores, which includes the gel pores and capillary pores. The wetting front progresses through the sample, saturating these small pores while bypassing the larger entrained and entrapped air voids as shown in Stages 2 through 5 in figure 1. Stage 5 defines the point where the gel and capillary pores are saturated whereas the entrained and entrapped air voids remain empty. The line drawn through points 1 to 5 in figure 1 defines the initial rate of absorption, which normally takes 10 to 18 hours to occur when the fluid is water under standard test conditions (Todak, Lucero, and Weiss 2015).



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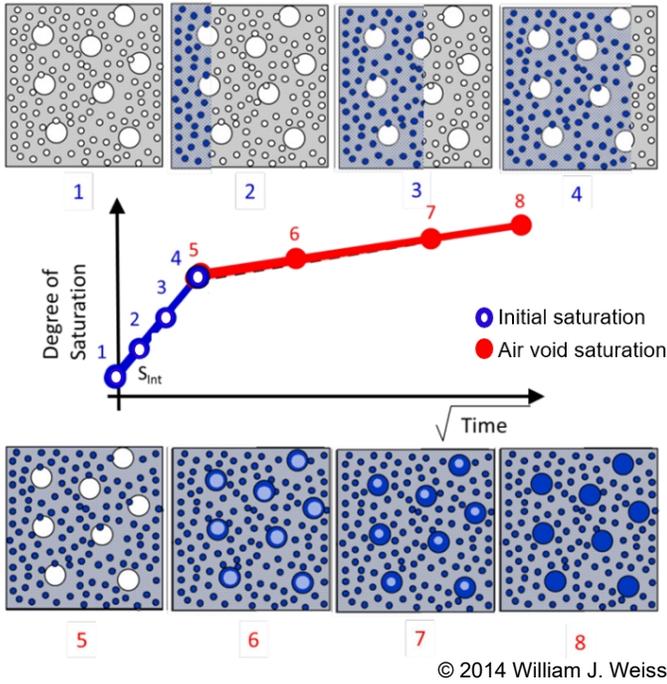


Figure 1. Illustration of water absorption into concrete during sorptivity test (note: initial saturation [stages 1-5] is characterized by filling of gel and capillary pores, whereas secondary absorption [stages 5-8] is characterized by filling of entrained and entrapped air).

As fluid continues to be adsorbed, the larger entrained and entrapped air voids become progressively saturated as illustrated in Stages 6 to 7, until complete saturation occurs at Stage 8. The line drawn through points 5 to 8 in figure 1 illustrates the secondary rate of absorption, which can take months to years before Stage 8 is reached (Todak, Lucero, and Weiss 2015).

A network of uniformly dispersed entrained air bubbles (such as shown in figure 2) can provide the needed empty space to relieve pressures generated as the concrete freezes. Because of their large size, entrained and entrapped air bubbles are the last space to saturate in concrete, remaining largely unsaturated under normal service conditions. It is widely recognized that concrete that is saturated below a critical level will not be damaged from freeze-thaw cycles because enough of the larger pores in the concrete are empty and provide adequate space to accommodate the hydraulic and osmotic pressures that develop as ice forms. But if this same concrete undergoes freezing and thawing in a critically saturated state (somewhere between 75 to 91 percent saturation with the most recent research pointing to a value of around 86 percent saturation), damage will occur even in a single freeze-thaw cycle, irrespective of air-void volume (Fagerlund 1977; Yang, Weiss, and Olek 2007; Li et al. 2012).

The role of entrained air voids in protecting concrete against freeze-thaw damage is to provide additional void space that largely remained unsaturated. As shown in

figure 3 (Todak, Lucero, and Weiss 2015), increasing the volume of entrained air decreases the overall degree of saturation at the inflection point that occurs when gel and capillary pores are saturated (stage 5 in figure 1). This reduces the degree of saturation below critical levels, illustrating one of the key principles explaining why entrained air enhances freeze-thaw durability (Todak, Lucero, and Weiss 2015).

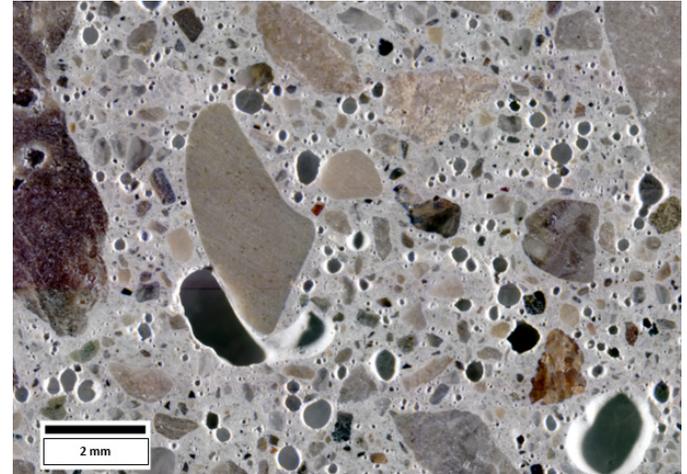


Figure 2. Stereo micrograph of entrained air voids (spherical bubbles) in hardened concrete; larger, irregular voids are entrapped air.

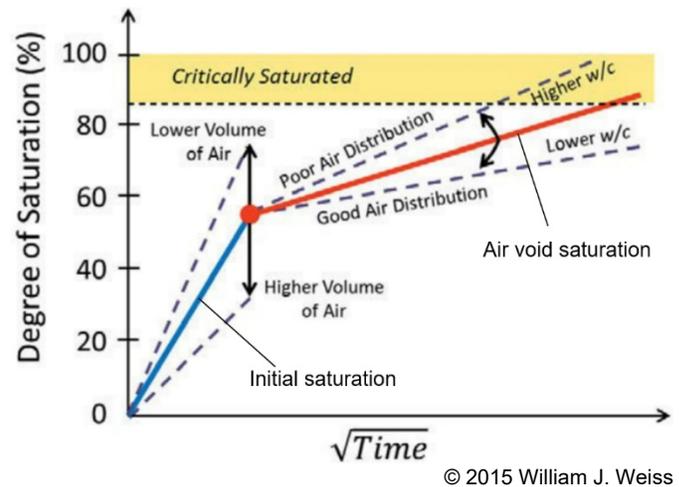


Figure 3. Illustration of the effect of volume of entrained air and w/cm on degree of saturation during a sorptivity test.

The water-to-cementitious materials ratio (w/cm) directly impacts the volume of the capillary pores in the concrete, which in turn directly impact the rate at which fluid is absorbed and transported. Concrete made with a high w/cm has an increased volume of capillary pores, which saturate relatively quickly resulting in an increased initial rate of absorption (Todak, Lucero, and Weiss 2015). Furthermore, as illustrated in figure 3, concrete with a high w/cm has increased permeability, allowing fluid to more easily pass through the concrete resulting in more rapid

saturation of the air voids (Castro, Bentz, and Weiss 2011). Thus, concrete with a high volume of entrained air and a low w/cm will take a very long time to reach critical saturation, whereas a concrete with a low volume of entrained air and high w/cm may quickly reach critical saturation.

HOW IS AIR ENTRAINED IN CONCRETE?

Air is entrained in concrete during batching either through the use of air-entraining cement or through the addition of an air-entraining admixture (AEA) (AASHTO M 154, ASTM C260/C260 M). The most common AEAs are composed of one or more of the following materials (Kosmatka and Wilson 2016):

- Wood resin (i.e., Vinsol resin).
- Sulfonated hydrocarbons.
- Fatty and resinous acids.
- Synthetic materials, including detergents.

AEAs are surfactants that create stable air bubbles in the fresh concrete as it is mixed. These bubbles remain once the concrete has hardened and ideally are uniformly

dispersed throughout the mortar phase in the concrete (see figure 2). The stiffness of the concrete mixture, the type and duration of mixing, and many other factors are influential in the formation of the entrained air. Excellent summaries of these factors are provided by Nagi et al. (2007) and by Kosmatka and Wilson (2016).

HOW MUCH AIR IS NEEDED TO PROTECT THE HYDRATED CEMENT PASTE IN CONCRETE?

Guidance provided by the American Concrete Institute (ACI 2016) indicates that the required air content to protect the hydrated cement paste is dependent on both the freeze-thaw exposure condition (presented in table 1) and the paste content (or mortar fraction) in the concrete (which is most often related to the nominal maximum aggregate size, as shown in table 2). Table 2 shows that as aggregate size decreases (mortar fraction increases), the total air required to protect the concrete increases. ACI mixture proportions are based on an assumption of angular coarse aggregates; thus, it is sometimes possible to reduce the required air content by approximately 1 percent if rounded aggregates are used. Additionally, more air may be required for pavements subjected to heavy deicer use.

Table 1. ACI freeze-thaw exposure classes (ACI 2016).

Exposure Class	Severity	Condition
F0	Not Applicable	Concrete not exposed to freezing and thawing cycles
F1	Moderate	Concrete exposed to freezing and thawing conditions, but very low probability of concrete being near saturation at time of exposure ¹
F2	Severe	Concrete exposed to freezing and thawing conditions, with a high probability of concrete being near saturation at time of exposure, but no deicing chemical exposure ²
F3	Very Severe	Concrete exposed to freezing and thawing conditions as well as deicing chemicals ³

¹ Examples are vertical surfaces above the level of snow accumulation and horizontal, elevated floors in areas protected from direct exposure to moisture.

² Examples are vertical surfaces below the level of snow accumulation, vertical surfaces with sufficient moisture exposure to allow the concrete to be near saturation prior to freezing, retaining walls or other vertical elements with one side exposed to moisture, and slabs-on-grade that are not protected from freezing

³ Examples are vertical surfaces that may have deicing chemical-contaminated snow piled against them, sidewalks or pavements that receive deicing chemicals, and concrete that receives frequent exposure to seawater and freezing and thawing conditions.

Table 2. Recommended air contents for different exposure class and nominal maximum aggregate size (based on ACI 2016).

Nominal maximum aggregate size, mm (in.)	Air Content Exposure Class F1, percent ¹	Air Content Exposure Class F2 and F3, percent ¹
9.5 (3/8)	7	7.5
12.5 (1/2)	7	7
19 (3/4)	6.5	7
25 (1)	6.5	6.5
37.5 (1-1/2)	6	6.5
50 (2)	6	6
75 (3)	5	5.5

¹ A reasonable field tolerance on air content is recommended as ± 1.5 percent.

HOW IS AIR ENTRAINMENT MEASURED?

It is the size and distribution of the air voids in hardened concrete that ultimately influence the durability of the concrete subjected to freezing and thawing. But because assessing the air-void system parameters in hardened concrete is time consuming and expensive, it is most common to measure the required total volume of air in the fresh concrete. Standard tests (or variations thereof) used by state highway agencies include:

- AASHTO T 152: *Standard Method of Test for Air Content of Freshly Mixed Concrete by the Pressure Method* (eq. ASTM C231) – The pressure method is the most commonly used test to assess the air content of paving grade concrete made with normal weight aggregates.
- AASHTO T 196: *Standard Method of Test for Air Content of Freshly Mixed Concrete by the Volumetric Method* (eq. ASTM C173) – The volumetric method (also known as the Roll-A-Meter) can be used to measure the total air in fresh concrete containing any type of aggregate, including lightweight or porous aggregates.
- AASHTO T 121: *Standard Method of Test for Density (Unit Weight), Yield, and Air Content (Gravimetric) of Concrete* (eq. ASTM C138) – The gravimetric method is based on the calculated difference of the actual density of the fresh concrete to the theoretical density of the concrete mixture (which uses the specific gravities of the materials for absolute volume) with no air present. The measured density is subtracted from the theoretical density determined from absolute volumes of the ingredients assuming no air is present, then divided by the theoretical density.

Although these tests methods are common, it is recognized the total volume of air in the concrete is not necessarily related to the air void size and spacing required to protect the concrete against freeze-thaw damage. Thus, alternate tests that make some assessment of the air-void system characteristics in fresh concrete, such as the Super Air Meter (SAM), are being investigated.

The SAM is standardized under AASHTO TP 118, *Provisional Standard Method of Test for Characterization of the Air-Void System of Freshly Mixed Concrete by the Sequential Pressure Method*. It is a modified version of an AASHTO T 152 pressure meter (Ley and Tabb 2013; Welch 2014), but instead of using a single testing pressure as is used in AASHTO T 152, the SAM uses sequential pressures to determine the volume of total air and to make an inference regarding the quality of the air-void system. The SAM obtains the same air content information garnered using the AASHTO T 152 test but also determines a SAM Number from the additional higher-pressure testing sequences. The SAM Number has been correlated to the air void spacing factor obtained through ASTM C457 and the Durability Factor (DF) of

concrete as assessed in AASHTO T 161 (Ley and Tabb 2013; Welch 2014). The failure criterion has been established for the SAM Number of 0.2 psi, which is roughly correlated to an ASTM C457 spacing factor of 0.008 inch and an AASHTO T 161 DF of 70 percent. Current results suggest that the SAM Number has a better correlation with AASHTO T 161 DF than it does to the ASTM C457 spacing factor (Ley 2015). The SAM method is currently undergoing evaluation by a number of states.

In hardened concrete, the air-void system characteristics can be directly characterized through manual assessment of magnified images of a polished concrete surface as described in ASTM C457, *Standard Test Method for Microscopical Determination of Parameters of the Air-Void System in Hardened Concrete*. ASTM C457 measures the total volume of air in the concrete and calculates other air-void system parameters that are related to freeze-thaw durability, including:

- Spacing factor – An index related to the distance of one air void to the next and recommended to be 0.008 inches (0.200 mm) or less.
- Specific surface – The surface area of air voids divided by their volume, recommended to be 600 $\text{inch}^2/\text{inch}^3$ (24 mm^2/mm^3) or greater.

The ability of the concrete to resist freeze-thaw damage increases as the spacing factor decreases (i.e., the air voids become more closely spaced) and as the specific surface increases. ASTM C457 discusses a desired maximum spacing factor of 0.008 inch (0.200 mm) for freeze-thaw resistance for concrete subjected to moderate exposure conditions, stipulating that this value can be higher for mild exposure and should be lower for severe exposure conditions, especially if the concrete is exposed to deicing chemicals.

ASTM C457 requires a trained technologist using a microscope and can take 3 hours or more to execute. Alternative automated methods in which digitally captured images are analyzed (e.g., RapidAir 457, flatbed scanner method [Peterson et al. 2001]) have been developed and are undergoing standardization. But automated methods still require extensive sample preparation and can only be conducted on hardened concrete. As a result, ASTM C457 or related automated methods are suitable for air-void system evaluation during the concrete mixture design phase or for forensic investigations but are not suitable for conducting QC or acceptance testing during construction since the results take days to obtain. More detailed information on these test methods is provided by Van Dam (2016b).

AIR ENTRAINMENT PROBLEMS

In most cases, the total air content of the fresh concrete is correlated with the air void size and spacing in the hardened concrete; thus, achieving the required air

content in the fresh concrete results in adequate resistance to freeze-thaw damage. But this is not always the case as there are times when the air content in the fresh concrete is acceptable just prior to placement but an unacceptable air-void system is not produced in the hardened concrete. These problems can be generally classified into the following two categories:

- Air-void system instability results in loss of air through handling and consolidation.
- An irregular air-void system is produced with regards to bubble size and spacing.

Air-Void System Instability

With regards to air-void system instability, the loss of a certain amount of air (1 to 2 percent) is common during the placement process when the concrete is pumped and/or consolidated (Whiting and Nagi 1998; Taylor et al. 2006; Ram et al. 2012). It is generally thought that the air that is lost is in the larger air bubbles, which are not as critical to freeze-thaw protection as the smaller bubbles. To address the air loss that occurs through the slipform paver, a number of highway agencies will either sample the concrete behind the paver (e.g., Kansas, Indiana) or require that the air content of the concrete placed on grade in front of the paver be higher than that required in anticipation of the loss of air (e.g., Wisconsin, Iowa). Of additional concern is that overvibration may lead to localized loss of air, which may result in the development of vibrator trails on a slipformed pavement. Under these conditions, the concrete in the vicinity of the vibrator is segregated, being largely devoid of coarse aggregate and often low in air and can exhibit localized freeze-thaw damage. Often this is considered a concrete mixture problem, although setting the frequency of the internal vibrators too high can be a contributing factor (Stutzman 1999; Taylor et al. 2006).

Aside from the loss of air due to placement, other factors that can contribute to air loss include (Nagi et al. 2007):

- Cement alkalinity – As alkalinity increases the air content increases for a given dosage of AEA.
- Supplementary cementitious materials (SCMs) – The use of SCMs can impact the air content. Carbon present in fly ash can significantly reduce the air content, as can SCMs that are more finely ground or that are highly porous.
- Chemical admixtures – AEA interactions with some chemical admixtures, particularly water-reducers based on co-polymer chemistry, have had negative effects on air void stability.
- Aggregates – Aggregate size and texture can influence air content, with crushed stone entraining less air than gravel aggregates. The particle size of sand is also influential with middle size fractions being most effective in entraining air (No. 30 to No. 100

sieves) whereas fine sands (less than No. 100 sieve) have negligible effect.

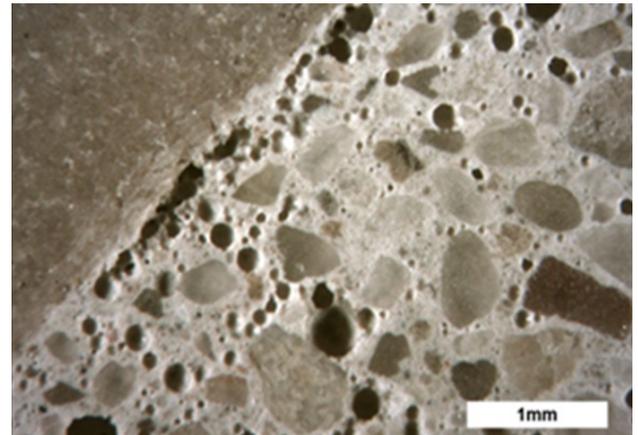
- Concrete temperature – For a given mixture, as temperature increases, a higher dosage of AEA is required to maintain the air content.

The air content of fresh concrete over time will provide a good indication of stability of the air-void system. Such testing is common when determining mixture proportions and should be repeated as materials change during construction. Furthermore, periodically testing after the paver will provide a good indication of air loss due to placement.

Irregular Air-Void Systems

A concrete may have acceptable volumes of air but still be susceptible to freeze-thaw damage because of an irregular air-void system. Irregularity may include:

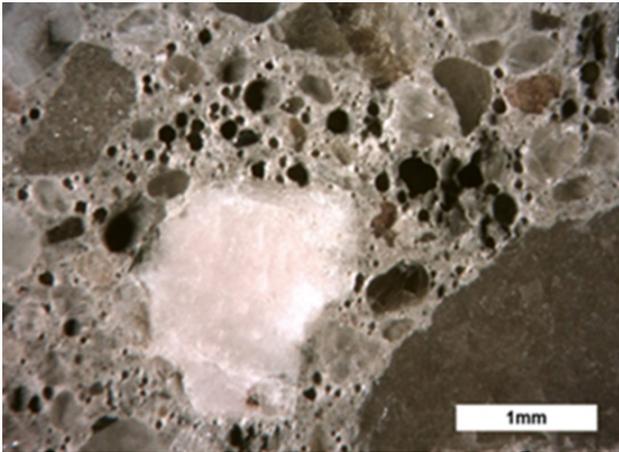
- Large bubbles spaced far apart – This can occur due to interactions between AEA and some chemical admixture, most notably polycarboxylate-based water-reducers.
- Air voids accumulating at coarse aggregate interfaces (see figure 4 [Ram et al. 2012]) – This can be due to retempering (the late addition of water) concrete containing non-Vinsol resin AEA (Kozikowski et al. 2005). Others have found that air voids can form along the aggregate interface if porous aggregates are batched dry of SSD (Buenfeld and Okundi 1999). Air void accumulation at coarse aggregate interfaces often results in loss of strength.



Source: WisDOT

Figure 4. Stereo micrographs showing air void accumulating at interface with coarse aggregate.

- Air void coalescence in paste (see figure 5) – Coalescence of air voids have been observed in some cases (Ram et al. 2012). The major cause of such clustering is uncertain, but it is thought to be due, at least in part, to insufficient concrete mixing. In some cases, the coalescence was observed in concrete with high air void content.



Source: WisDOT

Figure 5. Stereo micrographs showing coalescing in paste.

Addressing irregular air-void systems is difficult as the problem will likely not be observed through normal construction testing (other than strength loss that may accompany air void accumulation at aggregate interfaces). Such problems are usually only detected in the course of a study or forensic investigation in which petrographic analysis is conducted. Fortunately, such problems are thought to be relatively rare.

OTHER FACTORS

In addition to the total air content, the maximum w/cm is also typically specified to help enhance resistance to freeze-thaw damage. This is a recognition that the overall porosity decreases as w/cm decreases, resulting in a decrease in permeability and an increase in strength. ACI (2016) recommends a maximum w/cm of 0.50 for a freeze-thaw Exposure Classes F1, and 0.45 for Exposure Classes F2 and F3 for plain concrete (if reinforced, the recommended maximum w/cm for Exposure Class F3 is 0.40).

Additionally, if the pavement is hand-finished, the SCM content should be limited to a maximum of 25 percent fly ash or 50 percent slag cement, by mass of total cementitious materials. More recently, there has been recognition that formed and machine finished surfaces, such as slipformed pavement surfaces, are not greatly at risk of scaling and thus these limits are not considered applicable.

CONCLUDING REMARKS

Freeze-thaw damage in the concrete is mitigated primarily through the creation of an effective entrained air-void system in the concrete, in which the spherical air voids are sized and spaced sufficiently to relieve the stress generated through hydraulic and osmotic pressures. Current guidance suggests that the total volume of entrained air required to prevent damage is related to the overall volume of the mortar requiring protection and the freeze-thaw conditions to which the concrete is to be exposed. It is assumed that the total volume of air in the

fresh concrete is related to the size and spacing of the entrained air voids in the hardened concrete; an assumption that is not always true. Furthermore, as freeze-thaw conditions increase in severity, the maximum allowable w/cm is reduced, lowering the concrete permeability and increasing the strength.

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