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Assessing the Degree of Polish on Hardened Concrete Air Void Parameters

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Abstract: This study provides much needed insight regarding how the degree of polish on a concrete sample affects the hardened air void parameters. As required by ASTM C457, each hardened concrete sample assessed by any of its three procedures needs to be polished until light reflects off of the surface. However, there is currently little to no insight as to how various degrees of polish will affect the concrete air void parameters. This research aims to fill the gap in the literature by providing a step-by-step procedure, materials necessary, and most importantly, the effect of the degree of polish on the hardened air void system parameters. Four target air void percentages (control at 2%, low at 3 – 5%, medium at 5 – 7%, and high at >8%) were investigated. Two different polishing mediums (silicon carbide and diamond) were investigated at six different polishing pad grit sizes. The results show that the most economical and preferred polishing method uses diamond polish pads. The results also indicate that the first polishing step is crucial in producing a suitable surface for further analysis, which requires using the coarsest polishing medium. Therefore, the results indicate that any further polishing (at finer degrees of polish) is negligible in obtaining the hardened air void parameters following ASTM C457 procedures. The average percent difference across each polish pad grit size investigates was 3.8%. This value amounted to an average hardened air void difference of only 0.1 across all samples. Comparing the average hardened air void percentage across all polish pad grit sizes to the ASTM C231 fresh air percentage reveals an average difference of 6.7%, which constituted a difference of 0.3. Therefore, the results show non-statistically significant variations between any of the degrees of polish investigated, especially between the coarsest polishing medium and the finest polishing medium, which produces the reflective surface as stipulated in ASTM C457.
Keywords: Concrete; Durability; Air Voids; Characterization; Polish; ASTM Procedures.

1. Introduction

The impact of the hardened concrete air void system in concrete depends on the total volume, size, and dispersion of the air voids in the concrete system and their compatibility with various material properties. Properties affected by the air void system include workability, cohesion, density (fresh and hardened), strength, finish ability, and freeze-thaw resistance. The most crucial highway concrete parameter for long-term performance is the resistance to freeze-thaw durability. To effectively provide freeze-thaw resistance, the air void system must have a total volume of empty air voids that equals or exceeds the volume of water or ice not accommodated by space in the capillary pore system [1]. Additionally, the air voids must be dispersed throughout the cement paste so that nearly all of the paste is within an air-void system zone of influence [2 – 10]. The current method for studying the air void system in hardened concrete is ASTM C457 – "Standard Test Method for Microscopical Determination of Parameters of the Air-Void System in Hardened Concrete" [11]. This method, initially proposed by Brown and Pierson [12], consists of polishing a hardened concrete sawn sample and placing it under a microscope. The operator systematically makes measurements by counting the air voids that come into view. Statistical estimates are produced from the measurements that define the air content, paste content, air-void size distribution, and spatial dispersion. There are three methods described in ASTM C457: i) the Rosiwal linear traverse technique (Procedure A) and ii) the modified point-count method (Procedure B), and iii) the contrast-enhanced method (Procedure C). Although ASTM C457 is the standard test method for characterizing the entrained air void system in concrete, some significant sources of variability and uncertainty still exist in the test results. One primary source of variability in this testing standard is the degree of polish on the hardened concrete samples necessary to produce reliable and repeatable results. The standard states, "Lap the surface with successively finer abrasives until it is suitable for microscopical observations [11]." However, the phrase “suitable for microscopical observations” is subjective to the reader’s own interpretations of that phrase. The standard further elaborates by adding the following "A good surface for microscopical examination will show an excellent reflection of a distant light source when viewed at a low incident angle. There shall be no noticeable relief between the paste and the aggregate surface[11]." Although these sentences add further clarification, there is no discussion and no empirical evidence as to why that may be the case, how it may affect the results, and what if the polish is not to that degree or if the user is unable to achieve what the standard describes.

2. Research significance and objectives

The significance of this study is determining the impact of multiple variables on the hardened air void parameters as determined by all procedures found in ASTM C457. As previously stated, the current terminology of the standard is vague and subjective to the operator's interpretation of what constitutes a suitable surface and when they may see the reflection on the surface. The most crucial variable investigated in this study is the degree of polish necessary to produce reliable and repeatable hardened air void parameter results.

The specific research objectives are as follows:

1) Determine the degree of polish necessary to produce hardened air void results that are not statistically significant from each other.

2) Determine if any other variable may influence or impact the results from the first objective.

3. Literature review

The ability of concrete to survive a cold and wet environment is primarily dependent on the air void system in the hardened concrete [13]. It is crucial to accurately and quickly characterize the air void system as promptly as possible. The formation and source of pores in a hydrated cement paste system strongly influence freeze-thaw resistance. Calcium silicate hydrate (C-S-H) is a principal product of cement hydration, and Powers [6] recognized that this product determines the properties of cement paste. C-S-H porosity is about 25%, with pores known as gel pores, which are a few nanometers in size [14]. Because of the pores' small size, water cannot freeze inside them at typical temperatures, although the water in them may be supercooled [7]. During hydration, the voids left behind as the mixing water is removed from the system are capillary voids [15]. The sizes of these capillary pores range from approximately 5 mm to about 1 μm. The volume of capillary pores depends on the degree of hydration and the original water/cementitious material (w/cm) ratio [8, 14 – 17]. Air voids in hardened cement paste can be considered either entrapped or entrained. Entrapped air voids occur due to insufficient consolidation. These air voids are typically greater than 3/64 in size (1 mm) and irregular in shape [11]. Entrapped air voids are typically isolated from other entrapped air voids and provide no benefit to the concrete [7]. Entrained air voids are typically 10 to 1,000 μm in diameter and are primarily spherical. Entrained air voids are discrete and uniformly distributed and have little effect on concrete permeability.

Unlike most materials, which become denser during freezing, water expands and becomes less dense when the temperature falls below 32°F. The freezing point of water inside concrete pores depends on the pore sizes, the internal pressure, and the presence of solutes. At higher pressures (> 1 atm), the freezing temperature decreases. The presence of solutes such as K+, Na+, Ca2+, and Cl- in water also depress the initial freezing point [18]. The damage due to freezing action depends mainly on saturation degree [19]. Damage is unavoidable if the critical degree of saturation of approximately 86% for all voids is reached [20]. The following mechanisms are believed to be primarily responsible for freeze-thaw deterioration [14, 21]:

1) The hydraulic pressure is generated by freezing in capillaries.

2) The diffused supercooling gel water into capillaries after freezing.

3) Osmotic pressures result from the partial freezing in capillaries of solutions with local concentration differences.

4) The differential strains are due to localized shrinkage and swelling.

All of the mechanisms are influenced by the fluids' ability to travel through the system and saturate the pores. It is difficult for water to penetrate spherical air voids through capillary action due to surface tension forces; however, external pressures in the pore system may drive fluids into an air void. Damage, then, is significantly influenced by the fluid transport characteristics of the system and the size, shape, and connectivity of the pores [13].

Total air content is defined as the total volume of air voids expressed as a percentage of the bulk volume of concrete. This parameter has been the basis of acceptance testing since the AASHTO T152/ASTM C231 [22] test method was developed. Despite the critical parameter being the spacing factor, total air content was an adequate measure because the correlation between the two parameters was good. This correlation has been diminished with changes to system chemistry using different materials, increasing the need to measure other parameters that indicate potential durability, such as the Super Air Meter (SAM) number. Powers [5] suggested that air voids perform two functions in concrete: limiting the hydraulic pressure in the paste during the early age of freezing and limiting ice bodies' formation. The space between air voids is also expressed as the spacing factor becomes the most important factor based on the first function. As the water expands with decreasing temperatures (below ~39°F), it has to flow through saturated pores to find empty air voids before freezes. The spacing factor can differ between mixtures even with the same air content. Clustering is a phenomenon in which entrained air bubbles preferentially collect around aggregate particles. This clustering reduces the bond between the paste and the aggregate [1, 23, 24], and so the phenomenon has the potential to reduce compressive strength [25]. However, Riding et al. [26] reported no correlation between clustering and strength. Regardless, a system of tiny, stable bubbles close together is desirable to provide sufficient freeze-thaw resistance for concrete exposed to cold, wet weather. Spherical voids are more challenging to fill with water under capillary action than capillary pores. This action has the effect of reducing the degree of saturation of the system at any given time.

Unsaturated bubbles allow expanding water and ice to move without incurring pressures within the hydrated cement paste, which can ultimately crack and fail the concrete. The bubbles need to be close together to reduce the distance that expanding water has to travel, and they need to be small to reduce the impact on the mechanical properties of the mixture. The principal objective of using air-entraining admixtures (AEAs) in concrete is to provide and stabilize an air-void structure that can protect concrete from the deterioration brought by freezing and thawing. AEAs are readily adsorbed surfactants at air-water or solid-water interfaces and serve as bubble stabilizers. There are currently two explanations for how the air-void system forms during mixing. One explanation is that, during concrete mixing, air layers are trapped between the folding surfaces of the concrete, and the fine aggregate acts as a "three-dimensional screen" to hold air bubbles within the network of particles [1, 5, 24]. Powers [5,6] described another process in which air bubbles are formed in a vortex as the mixture is stirred. Mixing provides the energy to build the interface between air and liquid in large air voids and then splits the large voids into smaller bubbles.

4. Methodology

4.1 Materials

In order to properly assess the research objectives, multiple variables were investigated in addition to the degree of polish. For this investigation, one w/c was used (0.45) along with four target air void percentages (control at 2%, low at 3 – 5%, medium at 5 – 7%, and high at >8%). Two different polishing mediums were investigated (silicon carbide and diamond) at six different polishing pad grit sizes (260μm, 125μm, 70μm, 30μm, 15μm, and 6μm). A Type I/II ordinary portland cement was used for all mixtures regarding the specific concrete constituents. A locally available River Gravel (#67 grading) and River Sand that meets ASTM C33 requirements were used in all mixtures. The particle size distribution of these two aggregates can be seen in Figure 1.

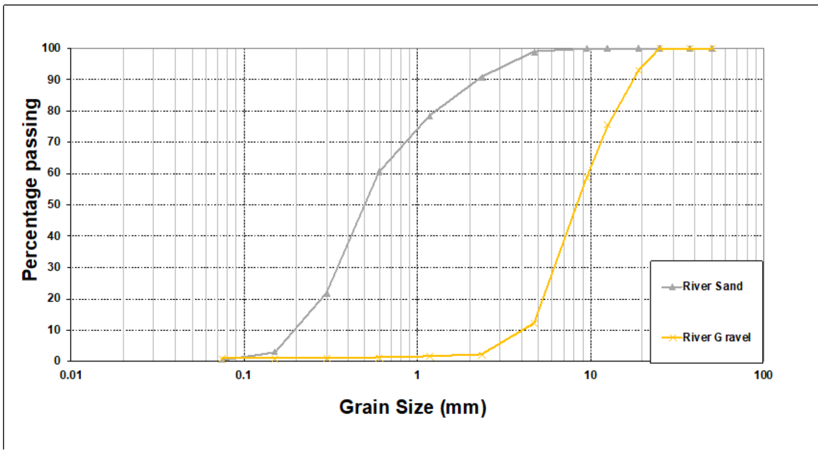

Figure 1. Particle size distribution for river gravel and river sand.

Only one AEA was used to provide consistent results, allowing the study to focus on the new characterization method. The air-entraining admixture that was used was SikaAIR, which meets ASTM C260.

Four straight cement concrete mixtures with no supplementary cementitious materials were produced in this study with the materials mentioned above. The mixtures were simple highway pavement mixtures aimed solely at producing various entrained air contents. A consistent slump of 3-5" was targeted to create similar workability between all mixtures. The air-entraining dosages were added at various ranges sufficient enough to provide low (3-4%), moderate (5-7%), and high (> 8%) fresh air contents in the produced mixtures. A non-air entrained mixture was also included as a reference in the study (control: 2%). Table 1 shows the mixture proportions of the four mixtures produced.

Table 1. Concrete mixture proportions.

Material	Control	Low Air	Medium Air	High Air
Type I/II Cement (lbs/yd^3)	565	565	565	565
Water (lbs/yd^3)	254	254	254	254
River Gravel (SSD) (lbs/yd^3)	1795	1757	1719	1643
River Sand (SSD) (lbs/yd^3)	1197	1171	1146	1096
Target Air (SikaAir)	2.00%	3.50%	5.00%	8.00%

The rationale for only using one w/c of 0.45 is that it is the standard w/c for concrete pavements that will be subjected to freeze-thaw conditions [27]. The mixture design proportions and constituents used were selected for similar reasons. The four different air contents were selected as they provided an even distribution of air void ranges for the investigation. Lastly, only two polishing mediums were selected at the six polishing levels as those are the most commonly available types and sizes for purchase in the United States.

4.2 Sample cutting

As discussed previously, multiple 4" (dia.) x 8" (length) concrete cylinders were cast and prepared for hardened sample preparation. Therefore, all hardened samples were cut from 4" (dia.) x 8" (length) concrete cylinders. A wet masonry saw was used in the cutting process, a standard piece of equipment found in a concrete materials laboratory. Two different saw blades were investigated; a) a typical 20" saw blade comes with the standard wet masonry saw (i.e., referred to as the standard blade); b) a 14" diamond cut-off wheel blade fits in the same category (i.e., referred to as the diamond blade). This study used two different blades to determine the speed and cut quality of the different blades. It is known in the industry that the standard blade typically leaves slight grooving along the cut surface following a complete cut of a concrete sample. In general, the smoother the cut from the saw blade, the less polishing time required in the polishing process; therefore, a diamond saw blade was investigated. When using either blade with the saw, a c-clamp was used to safely hold the concrete sample flush against the edge of the rolling table portion of the wet saw. This action helped to ensure that a relatively straight cut was achieved.

The cylinders were cut into nominal 0.75" thick samples. On average, one 8" long concrete cylinder would produce 6 – 7, 0.75" thick samples. The cylinder became unsafe to mount or hold by hand for further cutting. A single cut from the standard blade took approximately five minutes. A two-minute cut could be achieved, but the quality of the cut decreased. Even at a five-minute cut speed, the cut surface often exhibited slight grooving from the blade and a raised edge protruding from the cut surface. The raised edge is an issue as this edge will first need to be polished through before the majority of the sample will begin to be polished. The grooving was typically very fine and not as exaggerated as the raised edge. It could be seen with the naked eye and felt by hand. An example of the raised edge and grooving can be seen in Figure 2.

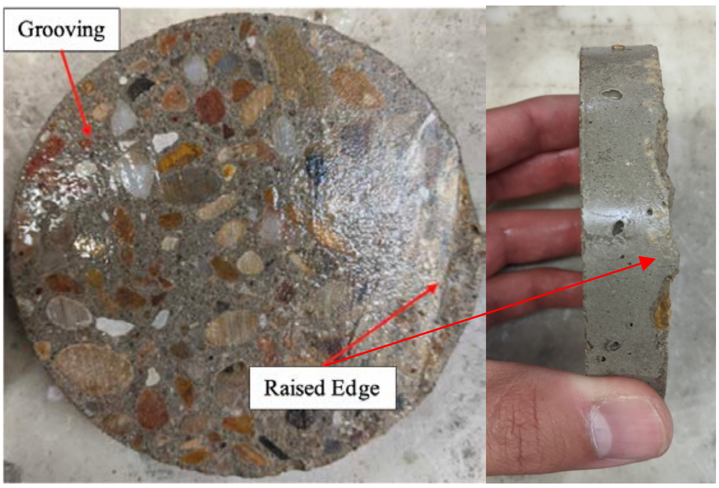

Figure 2. Standard blade cut quality.

A single cut using the diamond blade would take approximately two minutes, the quickest and safest cut speed noted for this blade and saw configuration. It was observed that the cut quality with the diamond blade was better than the standard blade. There was little to no visible grooving left from the saw, and the raised edge issue rarely occurred. An example of the cut quality from the diamond blade can be seen in Figure 3.

Based on these observations, it was concluded that of the two saw blades investigated in this study, the diamond blade is the best blade to use for cutting hardened concrete samples for hardened air void analysis. The cost of the diamond cut-off blade is lower than the standard blade, the cut speed is quicker than those provided by the standard blade, and the quality of the cut is superior.

Figure 3. Diamond blade cut quality.

4.3 Sample polishing

In this investigation, a standard auto-polisher with a 12" base can rotate clockwise at either 150rpm or 300rpm. The polishing arm can apply a pneumatically applied force of 30N – 600N (6.7lbs – 134.8lbs). An aluminum fixture was constructed to fit the polishing arm and mount a 4" diameter or 4" square concrete sample. The polishing arm rotates at 150rpm clockwise. The auto-polisher can automatically dispense water as a polishing lubricant. Once the desired force, base rotation speed, duration of polish, and desire to dispense water are selected, the polisher can be engaged. The polisher will commence for the desired duration.

Based on the literature, two popular mediums are used to polish concrete samples: Silicon Carbide paper polishing discs and diamond metal-backed polishing discs. Silicon Carbide paper polishing discs are typically sold in packs of 100. These polishing discs typically have an adhesive backing and must be applied to an accompanying metal support disc. The base of most auto-polishers is magnetic, and the support disc will magnetically attach to the base of the auto-polisher. However, once the Silicon Carbide polishing disc is spent, it will need to be removed from the metal support disc, and a new one applied. The diamond metal-backed polishing discs are sold individually (i.e., one blade per pack). However, these diamond polishing discs are pre-adhered to a metal backing; therefore, they do not require a metal support disc to attach to the polisher.

This investigation discovered that the first polishing step, using the coarsest polishing medium, is the most crucial in producing a suitable surface for further analysis. This first polishing step is necessary to produce a completely flat polish that removes all grooving and other uneven surfaces created from the saw cutting. Using the diamond blade discussed previously reduces the time required to achieve a completely flat polish from the first polishing step.

Both Silicon Carbide paper polishing discs and diamond metal-backed polishing discs were investigated in this study. It was observed that when completing the first polishing step, using the Silicon Carbide polishing discs at grade 80 (the coarsest option available) would require, on average, 2-3 polishing discs to achieve a completely flat surface. This action was completed at a recommended applied force range of 150N-300N (33.7lbs – 67.5lbs). This action was also a laborious process because a long polishing time could not be used, as the polishing disc had to be periodically checked to see if it had worn through. It was possible to see that the polishing discs were beginning to wear, as one side of the polishing disc is visible while polishing. However, it was not easy to interpret accurately while the polishing disc was spinning and wet. Therefore, the auto-polisher had to be stopped entirely, the polishing disc removed, dried with a forced-air hose, and then a decision to replace was made. If it was time to replace the Silicon Carbide polishing paper, it had to be removed from the metal support disc and a new one adhered. Removing the polishing paper from the metal support disc was completed with a handheld paint scraper tool, a razor blade scraper, and rubbing alcohol for any residue. This process could be sped up with an additional metal support disc, as one additional support disc could be pre-loaded with a new Silicon Carbide polishing disc and placed on the polisher. While the sample is polishing with the new polishing paper, the spent polisher paper could be removed and subsequently pre-loaded with the next Silicon Carbide polishing disc.

In addition to checking the polishing paper, the concrete sample needed to be checked to determine if an utterly flat polish was achieved. It was not easy to settle on a specific amount of time to stop the polisher and check the polishing paper and concrete sample, as the degree of polishing required per sample varied. This action can also vary on the force applied, the rpm of the polishing pads, and more specifically, the sample hardness, paste amount, and aggregates used in the concrete. With the samples produced in this study, a Silicon Carbide polishing disc would begin to wear out between 20-30 minutes on average at 300N (67.5lbs) force at a platen speed of 300rpm. As previously stated, 2-3 Silicon Carbide polishing discs were required to achieve a completely flat polish; therefore, at minimum, the first polish could be set for 20 minutes without stopping to save time. Once the sample was nearly complete, the polishing time was set to 2-5 minutes, depending on how close the sample was to complete. Following each short duration, the sample was checked. This procedure was followed to preserve the life of the polishing discs, as a limited amount was available for this study due to budget limitations. This process was more involved and required more operator time. However, if one had unlimited Silicon Carbide polishing discs, the polisher could be set to 30 minutes at 300N (67.5lbs) for three new polishing discs; on average, the sample would be utterly flat following this polishing regime.

It was observed that the diamond polishing discs were less labor-intensive and had a much longer life than the Silicon Carbide counterparts. Since the diamond discs are pre-metal backed, the polishing paper does not have to be removed or adhered to a support disc, so that process is completely removed with these polishing discs. Additionally, these polishing discs last much longer. In this investigation, approximately 50 surfaces were polished, and there was little to no sign of wear on any of the diamond discs. According to the manufacturer, 100s of samples can be polished per disc. It was also noticed that, on average, 20 minutes to polish a sample utterly flat with the coarsest diamond polishing disc (260μm) at 300N (67.5lbs) force at a platen speed of 300rpm. Due to the robust nature of the diamond polishing discs, higher forces have investigated an attempt to reduce the polishing time. The optimum configuration to reduce the polish time was 500N (112lb) at a platen speed of 300rpm with water as the lubrication. This configuration would produce a completely flat surface at an average polishing time of 10 minutes. Based on these observations, it was concluded that the diamond metal-backed polishing discs are worth any additional cost and are recommended for use in this process.

4.4 Final polishing procedures

Based on the sample polishing observations, the following procedures were developed.

1) Before polishing a sample surface, use a crayon to draw a grid on the surface spaced approximately ¼" x ¼," as seen in Figure 4. This action is necessary to help determine if the specimen surface is polished entirely flat.

a) The lines do not have to be perfectly straight or spaced but choose a color that contrasts with all features on the sample surface.

b) This is best completed on a dried sample surface.

2) Set the polisher force to 500N (112lbs).

3) Place a 260μm polishing disc on the polisher.

4) Polish one sample using a 260μm disc at a platen speed 300rpm and a force of 500N (112lb) for 10mins using water as lubrication.

5) Following the initial polishing, check the sample surface to see if all of the crayon markings have disappeared.

a) Sometimes, the crayon markings could be hidden by the water on the surface; therefore, it may be necessary to dry the sample with forced air to check if all markings are gone.

b) If no visible crayon markers are present, that surface is done with the 260μm disc and can be set aside for more delicate polishing. If any crayon markings are still visible, it is an incomplete polish. An example of an incomplete polish can be seen in Figure 5.

c) If an incomplete polish is noted, it is recommended to polish for an additional 10 minutes at 500N (112lb) at a platen speed 300rpm with water as the lubricant.

d) On average, one 10-minute pass at 500N (112lb) at a platen speed of 300rpm was necessary to achieve a completely flat polish.

6) Before moving to a more delicate polishing disc, dry the sample using forced air to remove the excess water and any polishing media remaining on the sample surface.

Do not put the air hose nozzle too close (approximately 2") to the sample surface, as it may damage the air void system.

For the study, further polishing was continued to determine the effect of each degree of polish. Therefore, the polishing was continued with diamond polishing discs sized 260μm, 125μm, 70μm, 30μm, 15μm, and 6μm. Multiple samples were prepared. The degree of polishing was assessed at each step. Therefore, multiple sample surfaces were prepared per concrete mixture at each polish pad grit size.

It should be noted that the 6μm polishing disc produces the glossy surface mentioned in ASTM C457. However, a glossy surface may not be necessary for the ASTM C457 procedure, thus saving time, money, and resources, which is the focus of this study. It has been determined that once the sample surface is polished entirely flat with the 260μm diamond polish disc, the force and polishing duration can be significantly reduced. The following procedure can be followed after the sample surface is polished entirely flat from steps 1-6 above.

7) Set the polisher force to 300N (67lbs).

8) Place a 125μm (or 70μm, 30μm, 15μm, 6μm) polishing disc on the polisher.

9) Polish the previously polished sample using the appropriate polishing disc at a platen speed of 300rpm and a force of 300N (67lbs) for 30sec using water as lubrication.

10) Dry the sample with forced air as previously described.

11) Repeat steps 7-10 with the next smaller-sized polishing disc until appropriate polish is achieved.

It should be mentioned that sometimes difficulty will be encountered when preparing the lapped surfaces, such that the air voids could begin to erode or elongate during the polishing procedure. A weak cement-paste matrix usually causes this. This effect was not observed with the samples produced in this study; therefore, no preparation for this effect was completed. However, suppose one desires to complete such a procedure. In that case, ASTM C457 describes a procedure in which carnauba is applied to the surface before polishing; then removed after all polishing procedures are completed. Other researchers [29, 30] have suggested applying a mixture of equal parts lacquer and acetone to the sample surface before polishing. After polishing is complete, the sample is soaked in acetone to remove any remaining lacquer/acetone mixture. This action could also be performed with a colored lacquer to help indicate when the sample has been polished entirely flat.

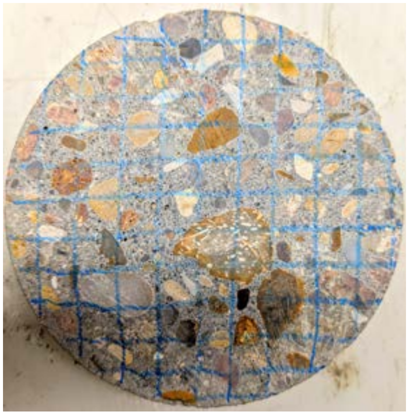

Figure 4. Example of the drawn grid with crayon.

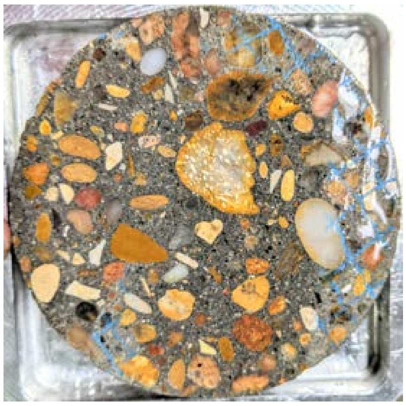

Figure 5. Example of an incomplete polish.

5. Results

5.1 Fresh and hardened properties

Before discussing and presenting the results regarding the degree of polish, it is pertinent to discuss and present the common fresh and hardened properties of the produced mixtures. This data is necessary to demonstrate consistency and commonality for the produced concrete. Table 2 shows the fresh and hardened property results.

Table 2. Fresh and hardened property results.

Property	Control	Low Air	Medium Air	High Air
Fresh Density (lbs/ft^3)	146	144	143	139
Slump (in)	3.75	4.25	3.5	4.0
Measured Air Content (ASTM C231) (%)	2.1	3.7	4.9	8.3
Air Content (SAM) (%)	2.3	3.4	5.2	8.7
SAM Number	0.61	0.58	0.39	0.12
7-day compressive strength (psi)	5086	4557	4328	3890
28-day compressive strength (psi)	6719	5723	5340	4280

The results shown in Table 2 are all as expected based on the literature, experiences, and the corresponding mixture proportions [27, 28]. The fresh density decreases with increased air content, which is expected since the air has negligible weight and less concrete material. The slump values were all within the target 3-5" range. The air values are also within the anticipated target range. The air content obtained from the ASTM C231 pressure method and the SAM meter appears to be in close alignment. The SAM numbers decrease with increased air content, which is expected based on the literature [27, 28]. A SAM number of 0.20 determined over 90% of the time whether the spacing factor is above or below the 0.008" limit [27, 28]. Therefore, an ideal SAM number is anything less than or equal to 0.20, which only the High Air mixture obtained. All other mixtures were above this value, which suggests the spacing factor is likely above the 0.008" spacing factor limit. The 7-day and 28-day compressive strength values were also as expected. All strengths showed a decrease in compressive strength with increased air content. The literature states that for every 1% increase in air content, a reduction in the compressive strength of about 500 psi occurs [28]. For the compression testing, 4" (dia.) x 8" (length) concrete cylinders were cast, cured, and tested.

5.2 Air void analysis and comparison

Following the sample polishing steps, the samples were analyzed according to ASTM C457-16 Procedure A (linear traverse method) and Procedure B (modified point and count method). These are the two main procedures used from this standard, as Procedure C (contrast-enhanced method) requires additional sample preparation steps, a flatbed scanner, and an analysis program. Most laboratories do not have the setup to complete this procedure; therefore, only Procedure A and B were investigated. The hardened air void analysis was completed using a Linear Traverse Machine commercially available in the United States. The machine was connected to a computer for data processing, which meets the requirements of ASTM C457. Although the system is called a Linear Traverse Machine, the provided software is geared towards completing a modified point and count procedure (Procedure B), in that the stage moves and stops at pre-determined points, and information is recorded based on what is observed at each point. A linear traverse procedure (Procedure A) can also be completed using the Linear Traverse Machine; however, the data must be collected, managed, and calculated with Excel (or other data management software) in combination with the linear traverse software. The Linear Traverse Machine hardware setup can be seen in Figure 6.

Figure 6. Linear Traverse Machine.

In order to ascertain the quality of each polishing level, Procedure A and B were completed on samples polished at 260µm, 125µm, 70µm, 30µm, 15µm, and 6µm, which is all of the diamond polish discs acquired for this study. Additionally, each sample has been analyzed a total of three times. Since the samples produced in this study are circular, there could be variability in the assessment regarding where the analysis begins relative to the sample. Both procedures require the starting point of a circular sample to be near the top and at one end of the initial traverse. However, slightly different results would be obtained if that starting point were different. A mark was placed on the sample side, and for the first assessment, the mark was pointed in the north direction, corresponding to the traverse stage, to control this and provide average results for each sample. ASTM C457-16 Note 8 describes the "East-West (E-W)" direction as the direction from the operator's left to right, and "North-South (N-S)" refers to the direction perpendicular to E-W. That is, the directions are analogous to those on a map. Therefore, procedures A and B were completed on one sample. The mark was oriented in the north direction. Then, the sample was rotated 45º to the east, such that the mark was oriented in the northeast direction. Then Procedure A and B were completed. Lastly, the mark was rotated an additional 45º to the east, such that the mark was oriented towards the east direction, and Procedure A and B were completed one last time on the same sample. The three data points for each polished surface were averaged and reported in Table 3 and graphically presented in Figures 7 – 10.

As seen in Table 3 and Figures 7 – 10, both procedures produced hardened air void percentages similar to the fresh air content measured via ASTM C231. Observing the hardened air void values across each polish pad grit size reveals no significant change between subsequent smaller grit sizes. The average percent difference across each polish pad grit size was 3.8%, with a range of 1.4 – 7.9%. This value amounted to an average hardened air void difference of only 0.1 across all samples. Comparing the average hardened air void percentage across all polish pad grit sizes to the ASTM C231 fresh air percentage reveals an average difference of 6.7% with a range of 2.1 – 14.6%. These fresh versus hardened air void percentage differences are also consistent with the reported values in the literature [2-5, 13-17, 20-25]. It is also observed that, on average, Procedure A produced slightly higher results than the ASTM C231 results, and Procedure B produced results that were, on average, below that of ASTM C231 results. This result is reversed with the High Air samples. This behavior is believed that due to the nature of the testing, Procedure B, pre-determined stops are established. The stops can miss an air void and be on the edge of an air void, and it is up to the operator's opinion whether to count the stop in an air void. For consistency purposes, the same operator completed all of the analysis, such that the decision was subject to the same individual. According to Hover [1], this decision process can have a higher effect on the measured air void percentage with specimens that contain lower air percentages, as the air voids could be smaller and more spaced out. This action provides further insight into why the Procedure B values were consistently lower than Procedure A values, aside from the High Air samples.

Table 3. ASTM C457 Procedure A and B Results (including fresh air properties).

Control - ASTM C231 Measured Air Content = 1.8%, SAM No. = 0.65							
Procedure A							
Polish Pad Grit Size	260µm	125µm	70µm	30µm	15µm	6µm	**AVG**
Air Void Content, %	2.1	2.2	1.9	2.1	2.2	2.0	**2.1**
Spacing Factor, in	0.0191	0.0203	0.0193	0.0221	0.0193	0.0212	**0.0202**
Specific Surface, in^2/in^3	422	472	459	430	410	430	**437**
Procedure B							
Polish Pad Grit Size	260µm	125µm	70µm	30µm	15µm	6µm	**AVG**
Air Void Content, %	1.7	1.6	1.6	2.0	1.7	1.7	**1.7**
Spacing Factor, in	0.0212	0.0195	0.0218	0.0158	0.0210	0.0183	**0.0196**
Specific Surface, in^2/in^3	437	420	451	411	431	419	**428**
Low Air - ASTM C231 Measured Air Content = 3.5%, SAM No. = 0.59							
Procedure A							
Polish Pad Grit Size	260µm	125µm	70µm	30µm	15µm	6µm	**AVG**
Air Void Content, %	3.7	3.5	3.7	3.8	3.6	3.7	**3.7**
Spacing Factor, in	0.0128	0.0131	0.0140	0.0155	0.0133	0.0120	**0.0135**
Specific Surface, in^2/in^3	591	599	585	572	583	573	**584**
Procedure B							
Polish Pad Grit Size	260µm	125µm	70µm	30µm	15µm	6µm	**AVG**
Air Void Content, %	3.4	3.3	3.3	3.3	3.2	3.4	**3.3**
Spacing Factor, in	0.0134	0.0148	0.0140	0.0151	0.0153	0.0132	**0.0143**
Specific Surface, in^2/in^3	572	582	581	573	582	571	**577**
Medium Air - ASTM C231 Measured Air Content = 4.8%, SAM No. = 0.39							
Procedure A							
Polish Pad Grit Size	260µm	125µm	70µm	30µm	15µm	6µm	**AVG**
Air Void Content, %	5.1	5.0	5.2	5.1	5.2	5.0	**5.1**
Spacing Factor, in	0.0096	0.0092	0.0098	0.0094	0.0098	0.0093	**0.0095**
Specific Surface, in^2/in^3	627	632	624	639	641	619	**630**
Procedure B							
Polish Pad Grit Size	260µm	125µm	70µm	30µm	15µm	6µm	**AVG**
Air Void Content, %	4.2	4.3	4.3	4.1	4.2	4.3	**4.2**
Spacing Factor, in	0.0110	0.0112	0.0109	0.0115	0.0107	0.0102	**0.0109**
Specific Surface, in^2/in^3	598	605	613	594	610	611	**605**
High Air - ASTM C231 Measured Air Content = 8.7%, SAM No. = 0.12							
Procedure A							
Polish Pad Grit Size	260µm	125µm	70µm	30µm	15µm	6µm	**AVG**
Air Void Content, %	8.5	8.2	8.3	8.4	8.4	8.5	**8.4**
Spacing Factor, in	0.0072	0.0074	0.0075	0.0071	0.0073	0.0079	**0.0074**
Specific Surface, in^2/in^3	723	711	722	709	728	735	**721**
Procedure B							
Polish Pad Grit Size	260µm	125µm	70µm	30µm	15µm	6µm	**AVG**
Air Void Content, %	8.9	8.9	8.9	9.1	8.5	9.0	**8.9**
Spacing Factor, in	0.0069	0.0071	0.0073	0.0068	0.0069	0.0064	**0.0069**
Specific Surface, in^2/in^3	769	772	775	789	742	782	**772**

The spacing factor and specific surface values did not significantly differ between the polish pad grit sizes. Both results are also as expected, in the appropriate range, and agree with the literature [2-5, 13-17, 20-25]. When comparing the two procedures for spacing factor, an average percent difference of 7.5% with a range between 3.1 to 13.7% was observed. While for the specific surface values, an average percent difference of 3.5% with a range of 1.2 – 6.7% was observed. The spacing factor values are consistent with the measured Super Air Meter (SAM) numbers. A SAM number of 0.20 or less typically produces a spacing factor of 0.008" or less. As seen in Table 1, the control, low air, and medium air mixtures obtained a SAM number above 0.20. All the mixtures have recorded a spacing factor above 0.008". Whereas the High Air mixture produced a SAM number of 0.12 and recorded an average spacing factor of 0.0069". As Ley et al. [28] indicated, this is typically the case approximately 90% of the time and was the case with the measured samples in this study.

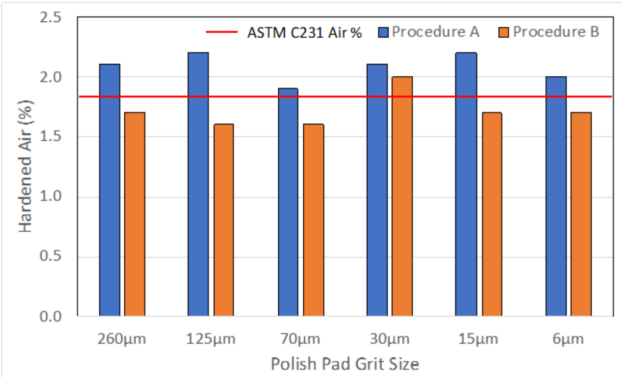

Figure 7. Control (2% Target) Hardened Air Void Comparison.

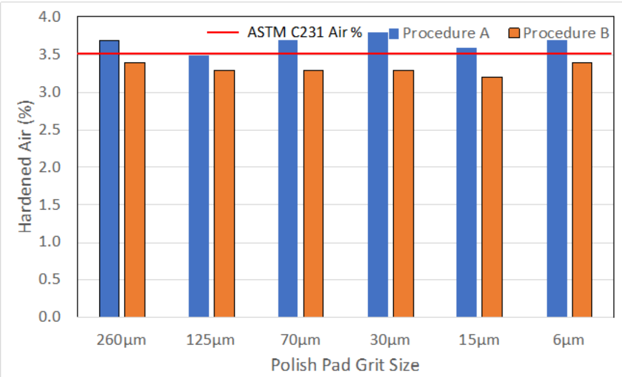

Figure 8. Low Air (3-5% Target) Hardened Air Void Comparison.

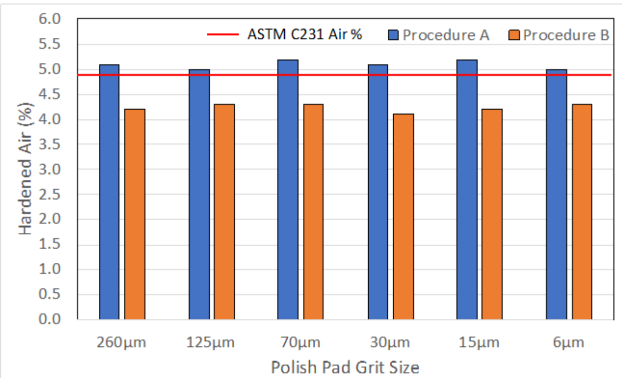

Figure 9. Medium Air (5-7% Target) Hardened Air Void Comparison.

Overall, the ASTM C457 characterization results were as expected and in an appropriate range. Additionally, the results indicate that, for the samples tested, it is unnecessary to polish any lower than 260μm, as long as the 260μm was polished as outlined in the procedures. This result indicates that time can be saved on the sample preparation step and cost, as the subsequent polish pads do not need to be purchased. It should be noted that the samples produced and polished in this study did not exhibit any air void degradation or elongation from the polishing process. Thus, it required no paste strengthening with lacquer or other means as described in ASTM C457 [11] and other authors [3 -5].

Additionally, all samples polished in this study had a minimum cured age of 28-days, which will lead to a more concentrated paste. Paste strengthening is likely required for younger samples. Additionally, Hover [1] indicates that faulty or incomplete specimen preparation can be a source of hardened air void characterization error.

Therefore, care should be taken to observe the quality of each subsequent polish step with a microscope or handheld magnifying glass to ensure no degradation has occurred.

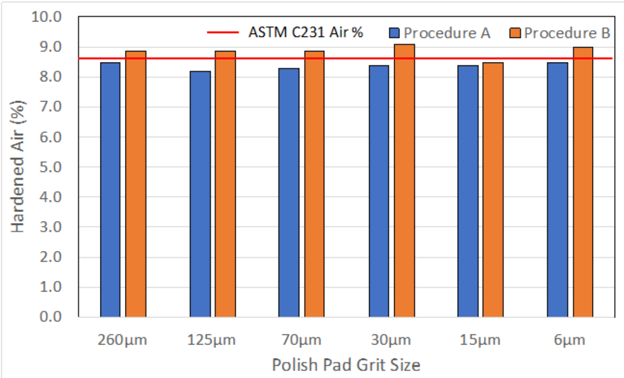

Figure 10. High Air (>8% Target) Hardened Air Void Comparison.

6. Conclusions

Based on the results and discussions in this study, the following conclusions can be made:

1) The degree of polish on a hardened concrete sample has no significant impact on the hardened air void parameters obtained by ASTM C457 (Procedures A & B). Therefore, an operator does not need to complete a degree of polish as outlined in ASTM C457.

2) Only a completely flat polish is necessary, which can be completed using the coarsest polishing pad available.

3) Other variables, such as the materials, mixture proportions, etc., had no significant impact on the degree of polish regarding obtaining hardened air void parameters.

4) A diamond blade saw produces the best cut quality on the samples investigated.

5) Diamond-based polishing pads are the most feasible polishing pad medium.

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