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Investigation into the Effects of Materials and Mixing Procedures on Air Void Characteristics of Fresh Concrete Using Air Void Analyzer (AVA)

ABSTRACT: The air void analyzer (AVA) was used to investigate the effects of concrete materials and mixing procedures on air void characteristics of fresh concrete. Twenty-seven batches of concrete were made with three mix proportions (with and without Class C fly ash or water reducer), and they were mixed with five mixing procedures (one-step mixing for 1, 2, or 4 min, two-step mixing for 4 min, and ASTM C 192 lab mixing procedures) and two sizes of pan mixers (0.014 and 0.042 m^3 or 0.5 and 1.5 ft^3). The air content, size distribution, specific surface, and spacing factor of all the batch mixtures were examined. The results indicated that incorporating 15 % Class C fly ash replacement or recommended dosage of a lignin-based water reducer into concrete generally reduced the spacing factor of air voids. The two-step mixing method (mixing mortar for 2 min first, and then mixing the mortar with coarse aggregate for another 2 min) produced a lower air void spacing factor than the one-step, 4-min mixing method (mixing all concrete materials together at once). For concrete mixed with the one-step mixing method, the air void spacing factor reduced with mixing time. For a given concrete mixture and mixing procedure, use of different sizes of mixers provided the mixtures with different air content and different spacing factor. The air void characteristics of the corresponding fresh and hardened concrete were also examined using the Type B pressure meter and RapidAir test methods, respectively. The correlations between the results from AVA, Type B pressure meter, and RapidAir tests were studied.

KEYWORDS: air void, fly ash, mixing, water reducer

Introduction

In cold climate regions, much concrete deterioration are associated with freezing and thawing (F-T) cycling and repeated applications of deicing chemicals. Properly entrained air is essential for the concrete. Many engineers have agreed that it is the well spaced air voids, rather than the total air voids, that play the vital role in improving the concrete frost resistance [1]. A great deal of work has been done in characterizing concrete air void system—measuring not only content but also the spacing factor of the air voids [2]. However, much of the work has been performed on hardened concrete until lately the new equipment, an air void analyzer (AVA), becomes available. The AVA device offers ability to measure the air content, specific surface, and spacing factor in fresh concrete within 25–30 min. With this information, adjustments can be made in the concrete batching process to ensure that proper air void structure is achieved during construction. Nevertheless, limited work has been done on characterizing the air void structures of fresh concrete using AVA, and current knowledge of the effects of various factors on the air void structures of fresh concrete is insufficient.

Previous research has indicated that the air void structure of concrete is generally formed during the concrete mixing process [3–5]. The concrete mixing process involves two primary processes that generate air in concrete. One is the infolding of air by a vortex action, as seen in the stirring of a liquid, and the other is the establishment of three-dimensional screens by the fine aggregate, which eventually leads to entrapment and holding of air bubbles within the network of falling and cascading masses [4]. It is clear that the air formation in concrete is significantly influenced by the concrete mixing (mixing energy and method).

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TABLE 1—*Properties of cementitious materials.*

Compound, %	Type I Cement	Class C Fly Ash
CaO	64.77	24.95
SiO_2	20.97	34.96
Al_2O_3	5.59	19.86
Fe_2O_3	2.27	5.4
K_2O	0.51	0.53
Na_2O	0.19	3.2
$(Na_2O)eq$	0.53	3.55
SO_3	2.99	-
LOI	0.82	0.29
Specific Gravity	3.14	2.66
Mean Particle Size (50 % volume), μm	25.00	13.60

Note: $(Na_2O)eq=Na_2O+0.658*K_2O$.

To facilitate the air entrainment, the entrapped air bubbles are often stabilized by the physio-chemical action of an air entraining agent (AEA). This air bubble stabilization is primarily dependent on the nature of the air bubbles (anionic, cationic, nonionic, or amphoteric) [6], their emulsification or foaming, thermodynamic and physical mechanisms [7], and cement solute concentration [8]. As a result, the complex air entraining process is also affected by many other factors, including concrete material characteristics, mixture proportions, and environmental conditions (mixture and mixing temperatures) [3].

In the modern concrete, supplementary cementitous materials (SCMs), such as fly ash, slag, and silica fume, are increasingly used because of their environmental benefits and excellent improvement in concrete durability. The SCMs generally have small particles and a large specific surface area, which may reduce the effectiveness of the air entraining agent (AEA) and also cause particle agglomeration. Thus, concrete containing SCMs may require additional air entrainment for F-T resistance and additional mixing time for reaching uniformity [9–11]. To improve concrete workability and other properties, various chemical admixtures are also increasingly employed into the modern concrete, some of which, such as water reducers (WR) and superplasticizers, can help cement dispersion effectively and require less mixing time for the concrete mixture to reach uniformity. Some of the chemical admixtures are also surfactants and facilitate air entrainment.

While great advances are made in concrete materials, the concrete mixing methods have had very little change. Although the individual effect of concrete materials and mixing methods on concrete air voids is known, limited research has been devoted to the study of the interaction between concrete materials and mixing methods as well as their combined effects on the air structure of fresh concrete. The present study was aimed at investigating the effects of materials and mixing procedures on concrete air void structures, especially on the size distribution and spacing factor of air voids in fresh concrete. The air void analyzer (AVA) was used to characterize the air void structure of fresh concrete, and the results were compared with those from RapidAir tests of the corresponding hardened concrete [12,13].

Materials, Mix Proportion, and Mixing Methods

The chemical properties of the cementitious materials used in this study are summarized in Table 1. Cement that met the requirements of ASTM C 150 [14] Type I and fly ash that met the requirements of ASTM C 618 [15] Class C were used. River sand with a fineness modulus (F.M.) of 2.92 and limestone with a nominal maximum size (NMSA) of 25 mm (1 in.) were used in all concrete mixes. An air entrainment agent (AEA), Daravair 1000, was employed in all mixes to gain an approximately 6 % air content for the concrete. A lignin-based WR, EUCON WR91, was applied to selected concrete mixes.

Three different concrete mixes were used: (1) a reference mix, (2) a mix with fly ash, and (3) a mix with WR. The proportion of the reference mix is presented in Table 2. Different from the reference mix, the mix with fly ash had a 15 % Class C fly ash replacement for Type I cement, and the mix with WR had an addition of the lignin-based WR (250 mL per 100 kg cement or 4 fl. oz per 100 lb cement). The water-to-cementitious material ratio (w/cm) of the three concrete mixes was 0.43.

The following mixing methods were used for each concrete mix:

(1) Standard mixing—The standard ASTM C 192 [16] lab mixing procedure was used as a reference.

TABLE 2—*Concrete mix proportions (SSD condition).*

Constituent	Proportion, kg/m^3 (pcy)
Cementitious materials	370 (624)
Water	159 (268)
Rivers and (F.M.=2.92)	877 (1478)
Limestone (NMSA=25 mm or 1 in.)	879 (1482)

Coarse aggregate were premixed with two-third of the designed mixing water, together with chemical admixtures, for approximately 30 s. Then, sand, cementitious materials, and the remaining water were added into the mixer. After all the materials were loaded, the mixture were mixed for 3 min, then stopped for 3 min, and mixed again for another 2 min (called 3-3-2 min mixing).

(2) One-step mixing—In the one-step mixing method, all concrete materials, including coarse aggregate, sand, cementitious materials, and mixing water, together with chemical admixtures, were loaded into a mixer and mixed at once. The mixing time of 1, 2, and 4 min was applied so as to investigate the effect of mixing time on the air void system of the fresh concrete (called 1, 2, or 4 min mixing).

(3) Two-step mixing—In the two-step mixing method, a mortar mixture, containing cementitous materials, sand, and half of the designed mixing water, together with chemical admixtures, were first mixed for 2 min. Concrete coarse aggregate and the remaining water were then added into the mortar and mixed for another 2 min (called 2-2 min mixing).

Twenty-four batches of the designed concrete were mixed with a 0.014 m^3 (0.5 ft^3) pan mixer at its full capacity. Three batches were mixed with a 0.042 m^3 (1.5 ft^3) pan mixer at its 75 % capacity. Both the mixers were manufactured by LANCASTER. During mixing, the pan and paddle of the mixers rotated in opposite directions. The rotation speeds of the pan and paddle were 13 rotations per minute (r/min) and 56 r/min for the 0.014 m^3 (0.5 ft^3) mixer and 11 and 44 r/min for the 0.042 m^3 (1.5 ft^3) mixer.

Testing Methods

After mixing, the air content of fresh concrete was immediately measured by a Type B pressure meter according to ASTM C 231, "Standard Test Method for Air Content of Freshly Mixed Concrete by the Pressure Method" [17]. Three 100 by 200 mm (4 by 8 in.) concrete cylinder specimens were then prepared according to ASTM C 192 [16]: one for the AVA test and two for the RapidAir tests.

An AVA test was conducted as soon as the concrete cylinder specimens were cast. Figure 1 shows the

FIG. 1—*Air Void Analyzer (AVA)*

FIG. 2—*RapidAir 457 system*

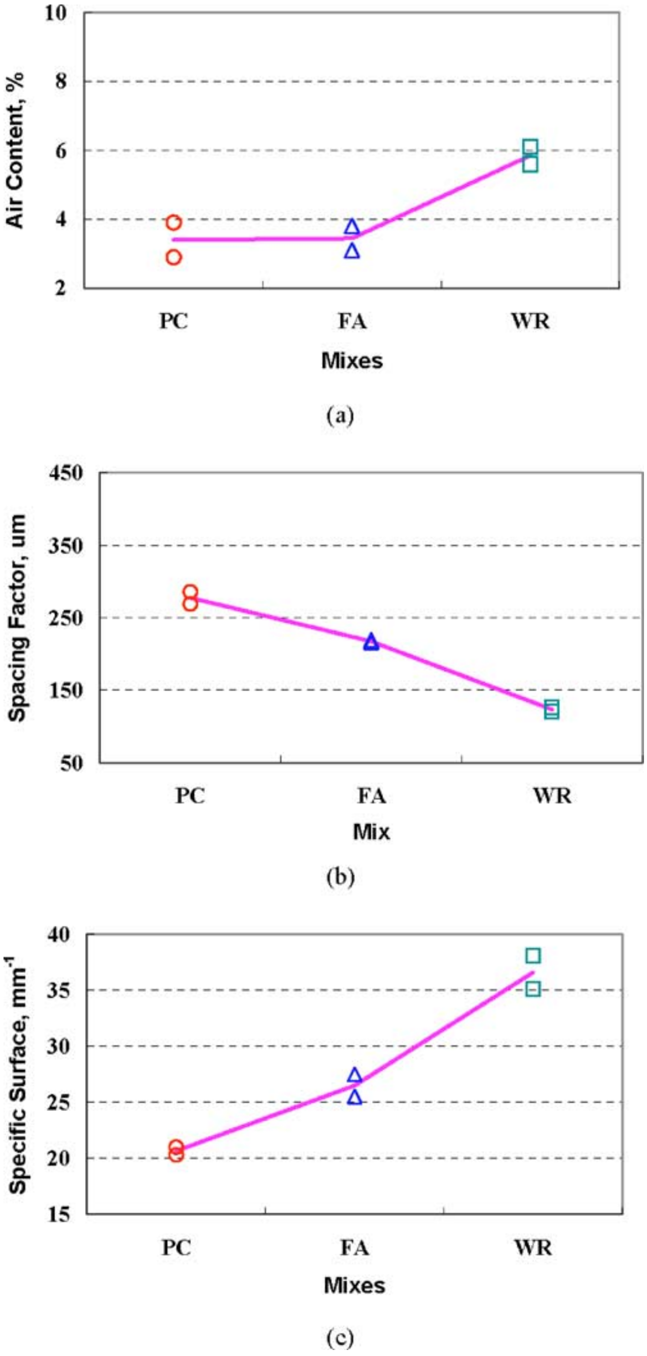
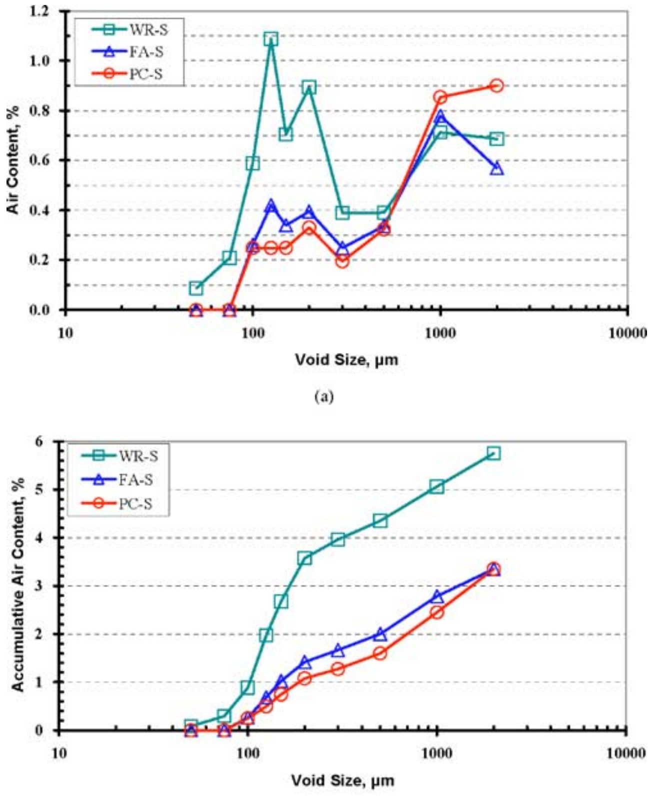


FIG. 3—*Effect of concrete materials on the AVA parameters (3-3-2 min. mixing)*



(a)

(b)

FIG. 4—*Effect of concrete materials on air void distribution (3-3-2 min. mixing)*

photo of the AVA device. It consists of two major parts: a base and a cylinder made with plexiglass and filled with a glycerin-based viscous liquid. To conduct an AVA test, a mortar sample was extracted from one of the three freshly-cast cylinder specimens using a 20 mL syringe that vibrated into the fresh concrete with a percussion drill. This mortar sample was then injected into the base of the AVA. After the injection, the viscous liquid was stirred for 30 s, thus releasing the air bubbles in the mortar sample. Depending on their size, the air bubbles raised at different rates. (Generally, the bigger air bubbles rose faster than the smaller ones.) When the raising air bubbles reached the top of the riser column, the change in mass caused by the buoyancy of the air bubbles was recorded by a sensor, which was connected to a computer, for 25 min. As a result, the AVA measured the amount and sizes of raising air bubbles with time, and the computer program converted the measurements into proper air void parameters, such as the total air content, size distribution, surface area, and spacing factor. It should be noted that only the air voids smaller than 3 mm (0.12 in.) were included in the computation.

RapidAir tests were performed on the concrete after 28 days of a standard fog room curing (23°C or 73°F, and >95 % RH). The air void structures of these hardened concrete specimens (two from each batch) were examined using the RapidAir 457 equipment. As shown in Fig. 2, the RapidAir 457 equipment, developed by Concrete Experts International, comprised a microscope objective mounted on a moving stage, a video camera, and a computer with monitor. It characterized concrete air void structures using a principle similar to the linear transverse method ASTM C 457 [18] "Standard Test Method for Microscopical Determination of Parameters of the Air-Void System in Hardened Concrete" [19,20].

To prepare for the RapidAir test, a 100 mm (length) by 75 mm (width) by 12 mm (depth) (4 by 3 by 0.5 in.) sample was cut from a concrete cylinder specimen, and it was polished according to the ASTM C 457 [18]. The sample was then brushed with a black-colored permanent marker and dried in an oven (50°C) for two days. After drying, the smooth, black surface of the sample was covered with a white powder (a blend of jelly and zinc oxide), which filled all open air voids on the surface of the sample. After the excess white powder was scraped off using a flat spatula, the sample, with white/bright air voids and black/dark in the rest of the surface area, was mounted onto the moving stage that was positioned under the video camera. The RapidAir system then automatically scanned the concrete plane section. The computer

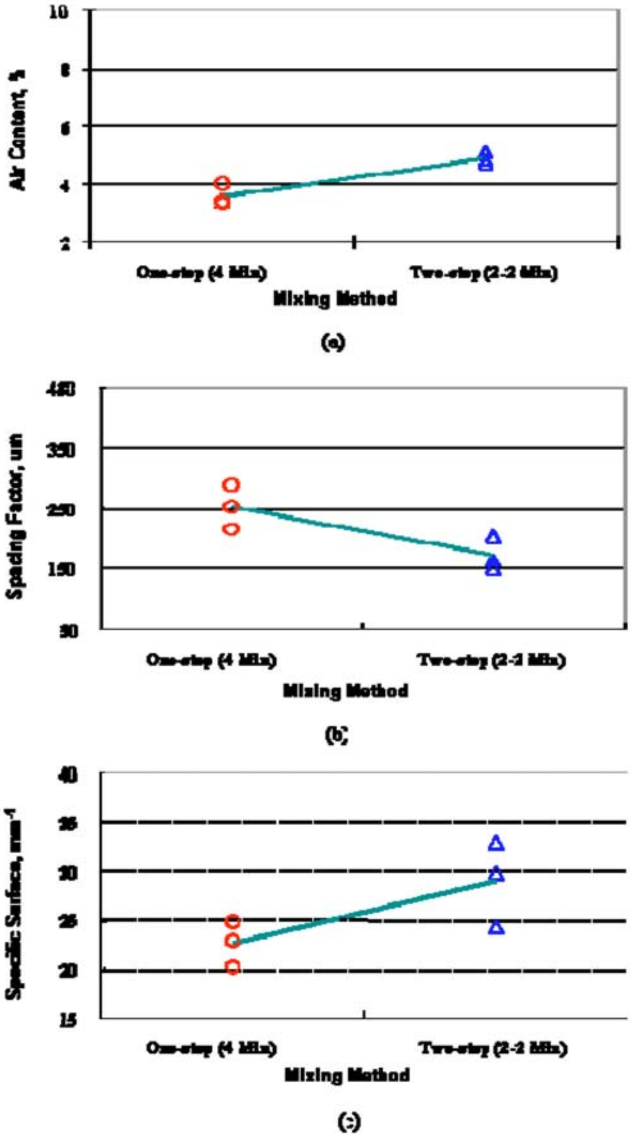


FIG. 5—*Effect of mixing sequence on AVA parameters (portland cement concrete)*

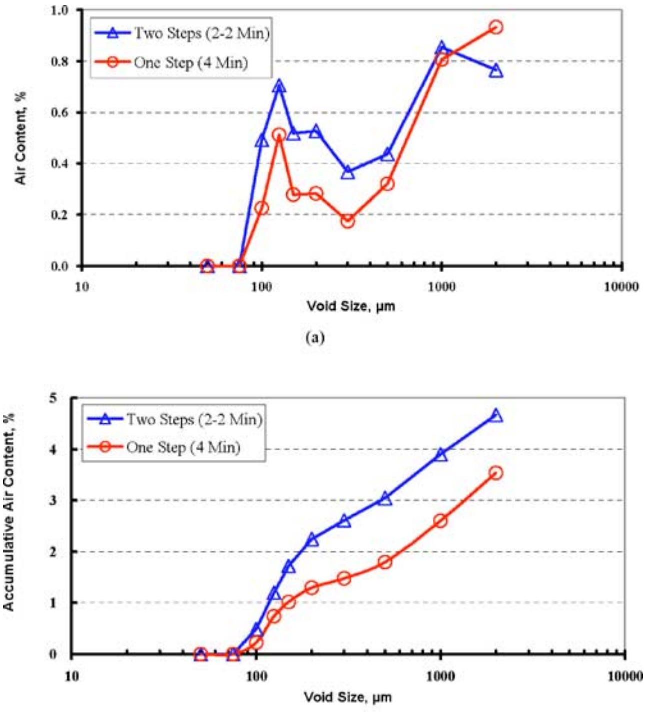
analyzed the amount and sizes of the white/bright air voids on each image (taken by the camera) as the moving stage moved, and the information was then converted to the air content, specific surface area, and spacing factor of the tested concrete based on ASTM C 457 [18]. In the present study, a threshold setting of 170 was used for the image analyses of all samples tested. This threshold level was set to achieve the best distinction of the actual air voids in concrete from the black background.

Results and Discussion

The AVA equipment used consisted of a computer program that is able to calculate the paste and concrete air content of the tested samples. In this paper, the air void parameters (such as spacing factor, specific surface, and size distribution) as presented below are all based on the air content of concrete.

Effect of Concrete Materials on Air Void System

The air void parameters (air content, spacing factor, and specific surface) and size distribution curves obtained from the AVA tests of three different concrete mixtures made with the standard mixing (3-3-2 min) procedures are plotted in Figs. 3 and 4, respectively. The measured air content was generally lower than what was designed partially because the air voids greater than 3 mm (0.12 in.) were excluded from the AVA test results.



(a)

(b)

FIG. 6—*Effect of mixing sequence on air void distribution (portland cement concrete, 4 min. mixing)*

As observed from Fig. 3, when compared with the concrete made with only portland cement as a binder, the concrete made with 15 % fly ash replacement had little change in the total air content (3.5 %), but it significantly reduced the spacing factor (from 275 to 220 μm) and increased the specific surface (from 21 to 26.5 mm^{-1}) of its air voids. The Class C fly ash used had a smaller mean particle size (13.6 μm, Table 1) and a lower loss of ignition (LOI) than portland cement ((25.0 μm), and it might modify the concrete air void system in several different ways. First, the fly ash might function as a water reducer, and it could release the mixing water entrapped by agglomerated cement particles, thus increasing available mixing water in concrete for air bubble formation. Second, the fly ash had a lower specific gravity (2.66) than the portland cement (3.14). Due to the 15 % (by weight) fly ash replacement, there were more fine particles in the fly ash concrete than those in the portland cement concrete. These fine, uniformly distributed fly ash particles would reduce the distance between the solid particles and increase the surface tension of the concrete pore solutions, thus in turn decreasing the risk of the air void coalescence and stabilizing small air voids in the concrete suspension system.

Figure 3 also illustrates that addition of WR into the reference mixture (PC) dramatically increased the total air content (from 3.5 to 6 %), reduced the spacing factor (from 275 to 125 μm), and increased the specific surface of air voids (from 21 to 36.5 mm^{-1}). The WR used (EUCON WR91) consisted of 10–20 % calcium lignosulfonate and 10–20 % sodium lignosulfonate, which was a surfactant and could help to entrain air. Since the WR increased the fluidity of the concrete, it also enhanced the air-entraining effect of AEA used [21].

Figure 4(*a*) indicates that addition of the WR generated much more small air voids (50–300 μm) while reducing large air voids (1000–2000 μm) in the concrete system. Fly ash replacement also produced a little more small air voids in the concrete system (100–300 μm) while significantly reducing large air voids (1000–2000 μm) in the concrete. Generally, the air voids with size less than 300 μm are desirable for concrete F-T resistance. Therefore, the WR addition and fly ash replacement might improve the concrete void structure.

In Fig. 4(*b*), the accumulative air void distribution curve of the WR concrete moved upward and leftward and the curve of the fly ash concrete moved leftward from the curve of the portland cement concrete. This also suggested that the WR addition and fly ash replacement produced finer air voids in the concrete. It was observed that the accumulative content of the air voids less than 300 μm was 1.3, 1.7, and 4.0 % for the concrete made with the portland cement, fly ash replacement, and WR addition, respectively.

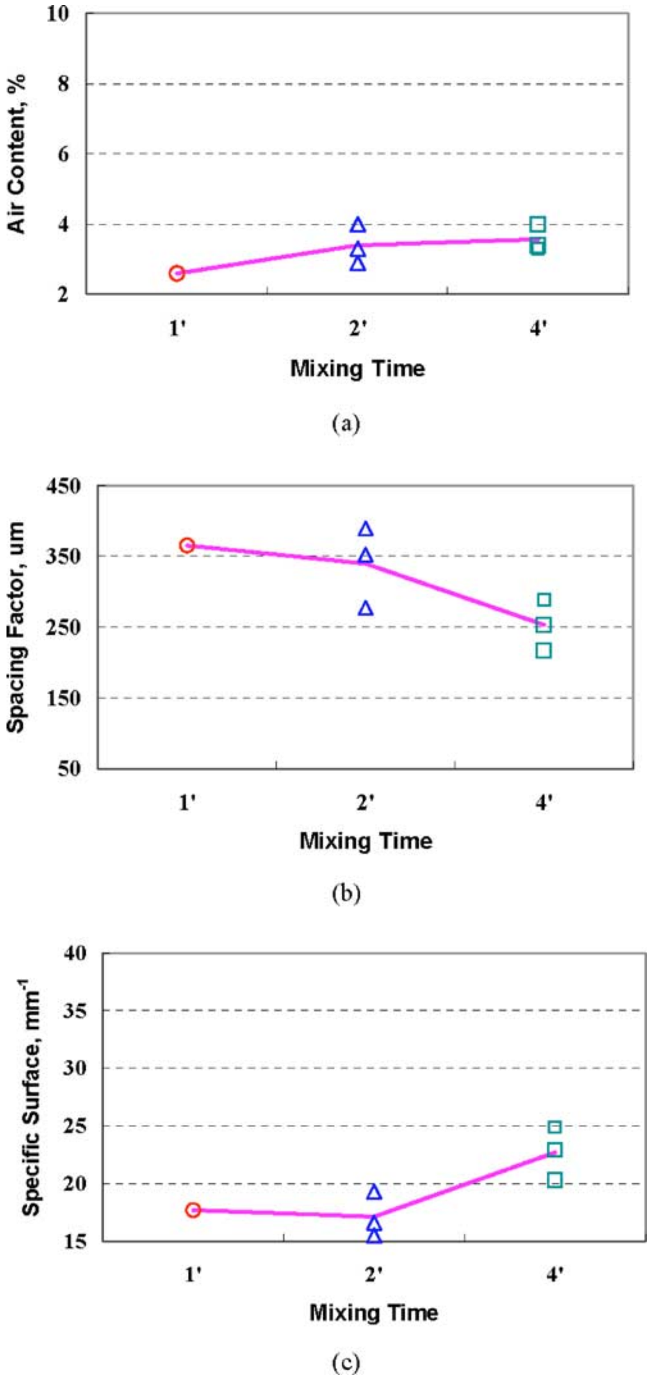


FIG. 7—*Effect of mixing time on the AVA parameters (portland cement concrete, one-step mixing)*

The one-step two-minute and four-minute mixing methods showed similar trends with the standard ASTM C 192 [16] lab mixing [22].

Effect of Mixing Procedure on the Air Void System

Figures 5 and 6 illustrate the AVA test results of the portland cement concrete mixtures mixed with one-step and two-step methods for 4 min. Compared with the one-step mixing procedure, the two-step mixing procedure produced the concrete with higher total air content, smaller spacing factor, and larger specific surface (Fig. 5). As illustrated in Fig. 6, the two-step mixing procedure generated much more small air voids (100–500 μm) than the one-step mixing procedure while it reduced the larger air voids (2000 μm). The accumulative content of the air voids less than 300 μm was 1.5 and 2.6 % in the concrete mixed with the one-step and two-step mixing procedures, respectively.

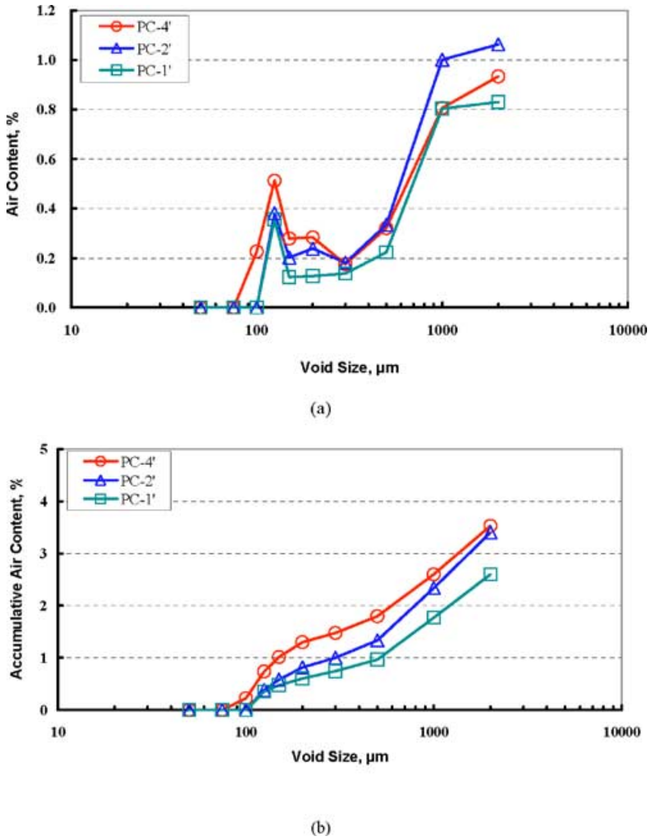


FIG. 8—*Effect of mixing time on air void distribution (portland cement concrete, one-step mixing)*

Since the same concrete materials, mix proportion, mixing equipment, and mixing time were applied, the differences in the air content and air void structures of these two concrete mixtures primarily resulted from only the mixing sequence. In the two-step mixing procedure, cement, sand, and half of the mixing water, together with AEA, were first mixed together for 2 min. Coarse aggregate and the remaining water were then added and mixed together for another 2 min (2-2 min). At the first step of this mixing, the mortar was more workable than the concrete mixed using the one-step mixing method, and the sand of the mortar uniformly suspended in the spaces between the cement particles and might have a "grid effect," preventing entrained air voids from escaping [23].

Effect of Mixing Time on the Air Void System

Three different mixing times (1, 2, and 4 min) were applied for the portland cement concrete mixed with the one-step mixing method, a given pan mixer, and a given mixing speed. Figures 7 and 8 illustrate effect of the mixing time on AVA test results. Compared with 1-min mixing, the 2-min mixing increased the total air content of concrete and reduced the spacing factor slightly. Compared with the 2-min mixing, the 4-min mixing did not increase the total air content of concrete significantly, but it did reduce the spacing factor and increased the specific surface greatly (Fig. 7). These results indicate that proper concrete air content can be achieved while a proper mixing duration is applied. Further increasing mixing time might not increase the total concrete air content but refine the air voids, thus increasing the air void spacing factor.

Figure 8 illustrates that 1-min mixing generated the lowest air content within all size ranges. When compared with the 1-min mixing, the 2-min mixing time produced a little more small air voids (150–500 μm) and much more large air voids (1000–2000 μm), which might be responsible for the increased total air content. The 4-min mixing produced more small air voids (100–200 μm) and a little more large air voids (1000–2000 μm). Based on Fig. 8(*b*), the content of air voids less than 300 μm was 0.7, 1.0, and 1.5 % in the concrete for concrete mixed for 1, 2, and 4 min, respectively.

According to Powers [23], during a mixing process, the shearing action of mixer blades continuously breaks up air bubbles into a fine system of spherical bubbles, and the probability of these bubbles becoming divided (or smaller) depends partly on the mixing time. A certain amount of time is required for the

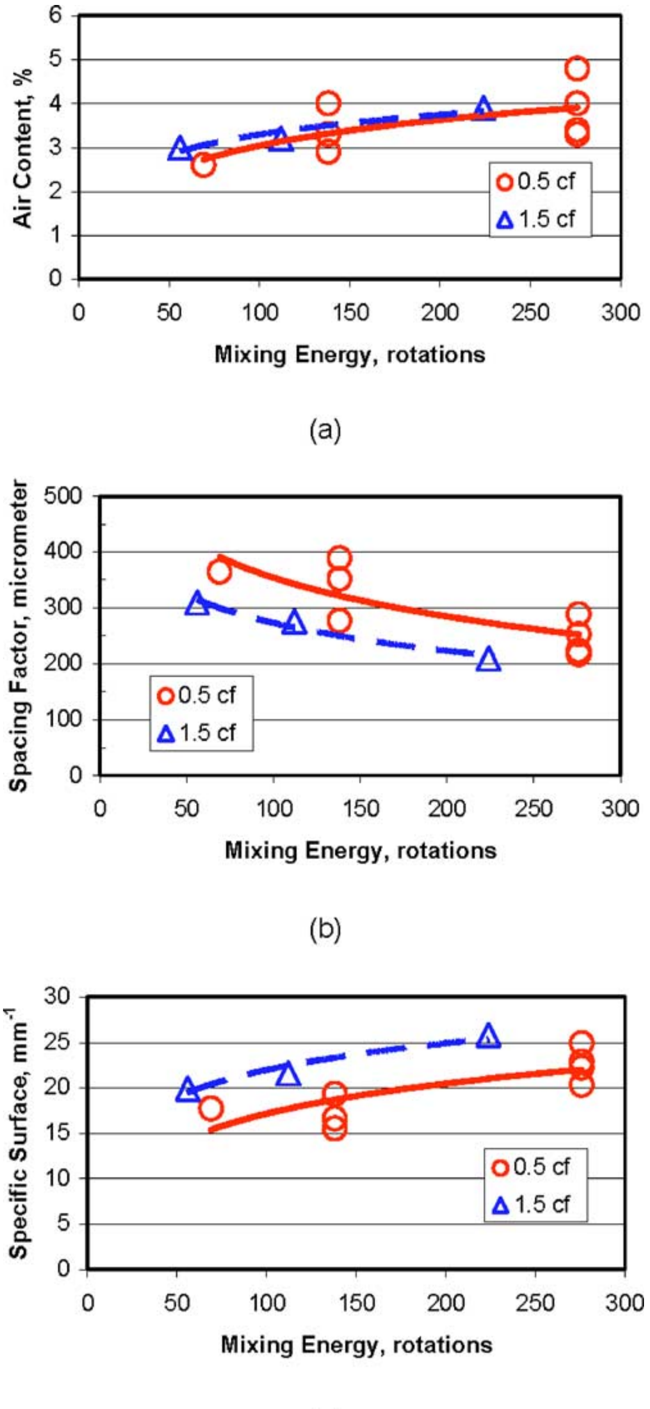
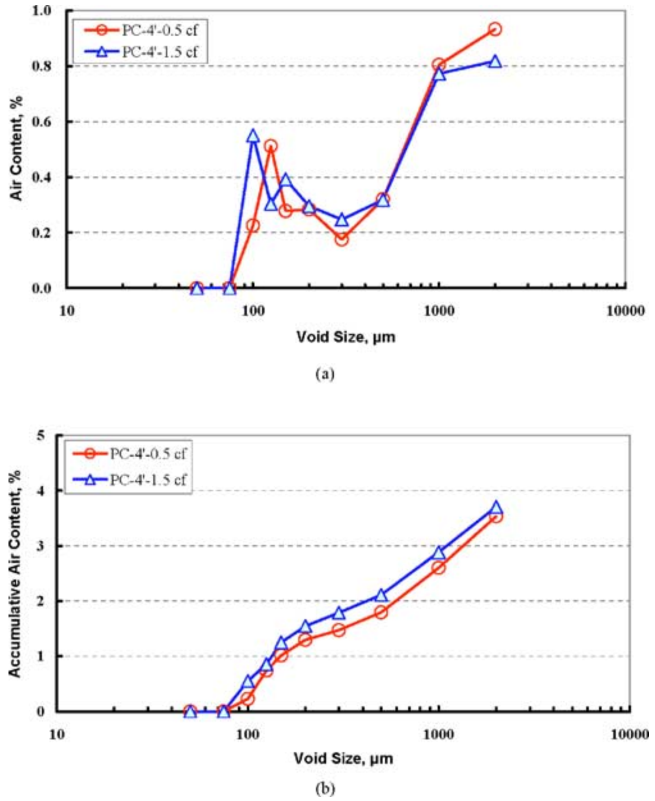


FIG. 9—*Effect of mixers on AVA parameters (portland cement concrete, one-step mixing)*

batch of concrete to be subjected to a maximum shear rate so as to produce a proper air void system in the concrete mixture. Insufficient mixing (such as one-step, 1-min mixing in this study) often results in low air content. Some concrete practice also indicates decreased air content in concrete with prolonged mixing. However, the present study demonstrates that the amount of desirable small air voids in the concrete increased with mixing time. Due to loss of stability, only the unwanted large size of air voids decreased with the mixing time.

Effect of Mixers on the Air Voids Distribution

Two pan mixers with a capacity of 0.014 and 0.042 m^3 (0.5 and 1.5 ft^3) were used for mixing of the portland cement concrete at 75 % of the mixer capacity. The total mixing speed (pan plus paddle rotation



(a)

(b)

FIG. 10—*Effect of mixers on air void distribution (portland cement, one-step 4 min. mixing)*

speed) was 69 r/min for the 0.014 m^3 (0.5 ft^3) mixer at full capacity and 56 r/min for the 0.042 m^3 (1.5 ft^3) mixer. The AVA test results of the concrete mixtures made with the two different mixers are plotted in Figs. 9 and 10.

Figure 9 once again gives evidence that the air content increased slightly, but the air void spacing factor decreased and specific surface increased considerably with increased mixing energy (also see Fig. 7). The mixing energy was defined as the production of mixing speed multiplied by mixing time. For given mixing energy, the total air ($\leqslant$3 mm) measured from the AVA tests of the concrete mixtures mixed with the two mixers was very close; however, the spacing factor of the concrete clearly reduced and the specific surface of the concrete distinctly increased when the large mixer was employed. According to Fig. 10(*a*), the 0.042 m^3 (1.5 ft^3) mixer made the distribution curve shift slightly leftward. That is, there were more small air voids and less large air voids in the mixture.

It should be noted that the results presented in this paper were from the lab-mixed, air-entrained concrete, which could be quite different from those obtained from the commercially produced concrete (mixed with a much larger mixer and higher mixing energy). The results from the lab-mixed, air-entrained concrete can be used as a good qualitative predictor of field concrete. However, further study is necessary to compare the lab results with field test results and to confirm these research findings.

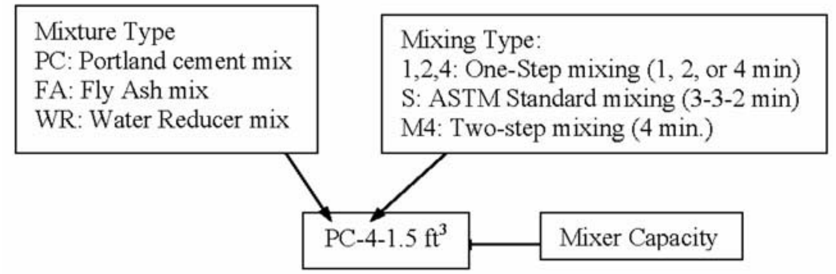
Relationship between AVA, Type B Pressure Meter, and RapidAir Test Results

Table 3 lists the air void parameters obtained from different test methods used. Statistical analyses were conducted to find the relationships between these test methods, and the results are shown in Fig. 11. The computer software JMP was used in the statistical analyses.

Figure 11(*a*) illustrates the relationship between the concrete air contents measured from AVA and Type B pressure meter tests. The linear regression of these test data had R^2 of 0.809, indicating that this linear relationship between the air contents obtained from the two test methods was reasonably strong, and the P-value of the linear regression was 0.0001 (smaller than 0.005), indicating that this relationship was statistically significant. It was noted that the air content from Type B pressure meter tests was generally

TABLE 3—*Test results for statistical analyses.*

Concrete Mixture	Concrete Air Content, % Pressure Meter	Concrete Air Content, % AVA	Concrete Air Content, % RapidAir	Spacing Factor, μm AVA	Spacing Factor, μm RapidAir	Specific Surface, mm^{-1} AVA	Specific Surface, mm^{-1} RapidAir
PC-S-0.5 ft^3	6.0	2.9	4.0	286	114	21.0	47.0
PC-S-0.5 ft^3	4.8	3.9	4.4	269	195	20.3	24.7
PC-4-0.5 ft^3	5.9	3.3	3.1	289	196	20.3	28.9
PC-4-0.5 ft^3	6.7	3.4	6.9	253	95	22.9	42.2
PC-4-0.5 ft^3	6.0	4.0	3.8	217	155	24.9	33.4
PC-2-0.5 ft^3	4.8	3.3	…	352	…	16.6	…
PC-2-0.5 ft^3	5.1	2.9	1.5	389	496	15.5	15.9
PC-2-0.5 ft^3	5.7	4.0	2.9	277	334	19.3	17.4
PC-1-0.5 ft^3	3.7	2.6	2.4	365	334	17.7	18.9
PC-M4-0.5 ft^3	5.7	4.8	4.2	203	174	24.3	28.4
PC-M4-0.5 ft^3	6.2	5.1	8.8	162	74	29.8	42.6
PC-M4-0.5 ft^3	7.1	4.7	4.5	151	157	32.9	30.5
PC-4-1.5 ft^3	4.8	3.9	5.5	209	126	25.8	34.6
PC-2-1.5 ft^3	4.7	3.2	3.1	276	215	21.6	28.2
PC-1-1.5 ft^3	4.2	3.0	3.1	309	244	19.9	24.7
FA-S-0.5 ft^3	5.3	3.8	6.8	216	68	25.5	60.0
FA-S-0.5 ft^3	5.3	3.1	5.7	219	139	27.5	32.9
FA-2-0.5 ft^3	4.6	3.6	4.7	267	199	21.0	23.6
FA-2-0.5 ft^3	5.2	4.2	4.3	254	222	20.7	21.8
FA-4-0.5 ft^3	6.6	4.1	5.5	190	108	28.0	43.2
FA-4-0.5 ft^3	7.3	5.0	5.0	210	185	25.4	26.3
WR-S-0.5 ft^3	8.3	5.6	4.3	121	178	38.1	27.3
WR-S-0.5 ft^3	8.4	6.1	10.2	126	62	35.1	44.3
WR-2-0.5 ft^3	10.4	9.5	7.2	97	147	29.9	26.2
WR-2-0.5 ft^3	8.5	9.0	8.8	99	103	31.3	30.7
WR-4-0.5 ft^3	10.6	8.2	4.7	100	164	33.8	30.5
WR-4-0.5 ft^3	10.4	7.9	7.8	105	97	33.5	36.6

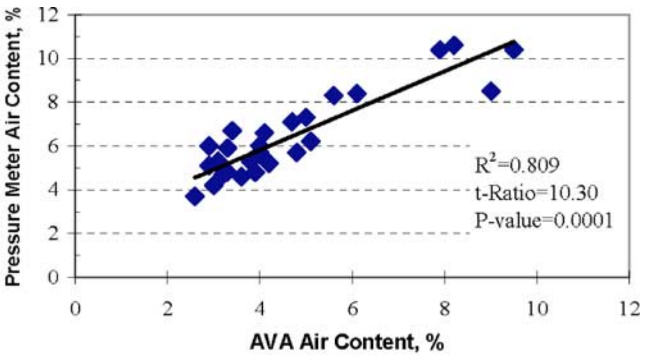


higher than that from the AVA tests, which was probably due to the facts that the vibration during the AVA tests released most entrapped air and the air voids greater than 3 mm (0.12 in.) were excluded from the AVA computation.

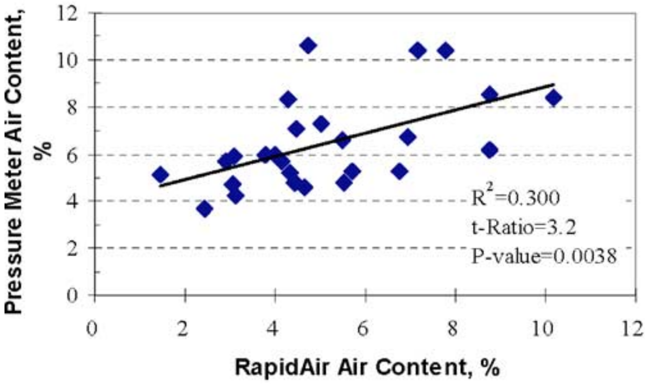
Figure 11(*b*) demonstrates the relationship between the concrete air contents measured by RapidAir and Type B pressure meter. The linear regression of these test data had R^2 of 0.300 and the P-Value of 0.0038 (smaller than 0.005). Although the linear relationship was not as strong as that between AVA and Type B pressure meter, the regression parameters (P-Value) indicated the linear relationship between the air contents from RapidAir and Type B pressure meter tests was still statistically significant. The RapidAir test seemed to have a very high dependency on the sample preparation and the threshold setting for the image analyses, which might be a cause of the weak relationship.

The AVA test results also provided more important information on the air void structure (spacing factor and size distribution). Figure 11(*c*) presents the regression of spacing factors obtained from AVA and RapidAir tests. This linear regression had R^2 of 0.489 and P-Value of 0.0001. Regardless of scattering of the data, these regression parameters (P-Value) indicated that the linear relationship between the spacing factors from these two test methods was still statistically significant.

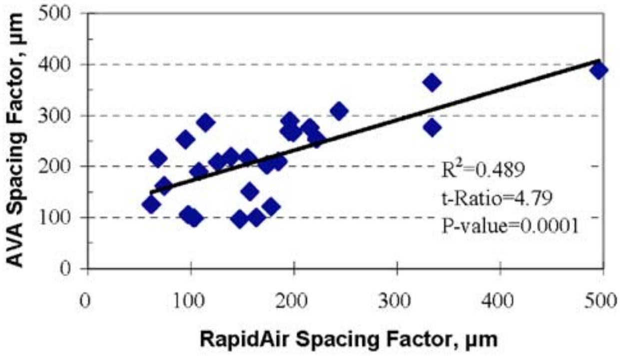
Due to the difficulties in the RapidAir sample preparation and the threshold setting for the image analysis, the RapidAir test procedure may need to be reevaluated and the relationships between the results



(a) Air content (Pressure Meter vs. AVA)



(b) Air content (Pressure Meter vs. RapidAir)



(c) Spacing factor (AVA vs. RapidAir)

FIG. 11—*Relationships between different test methods (pressure meter, AVA, and RapidAir)*

obtained from AVA and RapidAir tests need to be further verified. Another standard test method, such as ASTM C 457 [18], may be used in this verification to ensure the close relationship between RapidAir and ASTM C 457 [19,20].

Findings and Conclusions

The major findings from this study are summarized as follows:

1. AVA tests indicated that 15 % of fly ash replacement for portland cement reduced the air void spacing factor while providing little change in the air content of the concrete. Addition of a lignin-based water reducer significantly reduced the spacing factor while increasing the air content and air void specific surface of the concrete.
2. Compared to the one-step mixing method (mixing after loading all materials), the two-step mixing method (mixing mortar first and then adding coarse aggregate) produced a lower spacing factor for

a given mixing time, and it increased the amount of small size air voids while reducing the large air voids.

3. For given concrete materials, mixing equipment, and mixing procedure, concrete air content generally increased noticeably with mixing time (or mixing energy). More importantly, the concrete air void spacing factor reduced and specific surface increased significantly with the mixing time.
4. With given mixing energy (defined as the mixing speed multiplied by mixing time in the present study), a large mixer facilitated producing a better air void structure (with smaller spacing factor) than a small mixer.
5 The air content measured from the AVA tests showed a strong linear relationship with that measured from Type B pressure meter [17] tests. The air void parameters measured from RapidAir tests showed a weak, but still statistically significant, relationship with those measured from Type B pressure meter tests (air content) and AVA tests (air content and spacing factor). The RapidAir test procedure may need to be reevaluated, and the relationships between the results from RapidAir tests and from other tests need to be further verified.
6. AVA test results provided valuable information on the fresh concrete air void system. This test method can be recommended for further evaluation of concrete mixing, material compatibility, and quality control. Further study is necessary to verify the lab research results with field test results.

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