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Stability improvement of bubbles by entraining fine air in self-compacting concrete proportioned at factory scale

Anuwat Attachaiyawuth[1,*], Nipat Puthipad[2] and Masahiro Ouchi[2]

[1]Department of Civil Engineering, Faculty of Engineering at Sriracha, Kasetsart University Sriracha Campus, Chonburi, Thailand
[2]School of Systems Engineering, Kochi University of Technology, Kochi, Japan
[*]Corresponding author: anuwat@eng.src.ku.ac.th

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Abstract

Self-compactability enhancement by small bubbles has been developed for a decade. Those effective bubbles in concrete need to be ensured its stability. A full-scale experimental study was conducted on the stability of entrained air in air-enhanced self-compacting concrete (Air-SCC). The flow diameter and V-funnel time were measured based on the air content in the concrete immediately and 1 h after mixing. An air void analyzer was used to measure the diameter size of the entrained bubbles at the fresh stage. A water-dividing mixing method along with longer mixing time were used to increase the volume of small bubbles. The results indicated that the water-dividing method and 180 s mixing with a simple method effectively entrained small bubbles in mixtures using superplasticizer blended with retarder. That effective procedure could increase volume of small bubbles approximately 3.0%. Fine bubbles were defined by the high value of specific surface area ($\alpha > 20$ mm^2/mm^3). Concrete containing air bubbles with a high α value had a reduction rate less than 1% of air content at 1 h. The authors have succeeded to maintain the air lost less than 1% of the designed value as this affected both the self-compactability and freeze-thaw resistance of concrete. These findings will be beneficial in designing or producing self-compacting concrete, especially in a cold environment.

Keywords: Air-SCC, Air size distribution, Stability improvement, Specific surface area, Stability of entrained air

1. Introduction

Self-compacting concrete (SCC) was invented in 1986 by Prof. Okamura and his team [1] to solve a durability problem and the lack of skilled workers. However, it is necessary to increase the cement content to approximately 2 times higher than that of normal concrete, as shown in Figure 1. Some researcher proposed the optimum design method for this concrete [2]. Attempts have been made to replace the cement content with pozzolan materials, especially fly ash, to reduce the cost of the cement and to increase the workability of the concrete [3-9]. Highly flowable concrete has been used with the addition of various types of fiber to improve the mechanical properties of structures [10-14]. Furthermore, it has been applied as an innovative materials used for 3D-printed concrete [18]. Plenty of previous research attempted to improve self-compatibility at the same time with reducing natural materials.

An interesting option to improve the self-compactability of SCC is entraining fine bubbles (approximately 10%) which is called air-enhanced self-compacting concrete (Air-SCC) [16]. The mix proportion of this concrete are shown in Figure 1. The cement content can be significantly reduced because flowability is improved by the ball bearing effect caused by the fine air bubbles [16]. Therefore, the volume of fine aggregate can be increased above the level in conventional SCC. However, the coarse aggregate content must be limited to the same level as in conventional SCC. The volume of fine bubbles can be increased by incorporating fly ash using various mixing procedures, resulting in satisfactory results for self-compactability [17,18]. The improvement in self-compactability was achieved by effectively eliminating large bubbles by adding defoaming agent and entraining fine bubbles using the water-dividing method [19-21]. The stability of the entrained air is a concern for Air-SCC because it affected freeze-thaw resistance. The critical size for bubbles that reduced the stability of the entrained air was a diameter greater than 1,000 μm [22]. The viscosity of the mixture could be optimized to maintain the stability of the entrained bubbles [21]. It is necessary to verify the results obtained from laboratory with full-scale experiment to ensure that the stability of entrained air can be improved by entraining fine bubbles in Air-SCC. This work can verify that point.

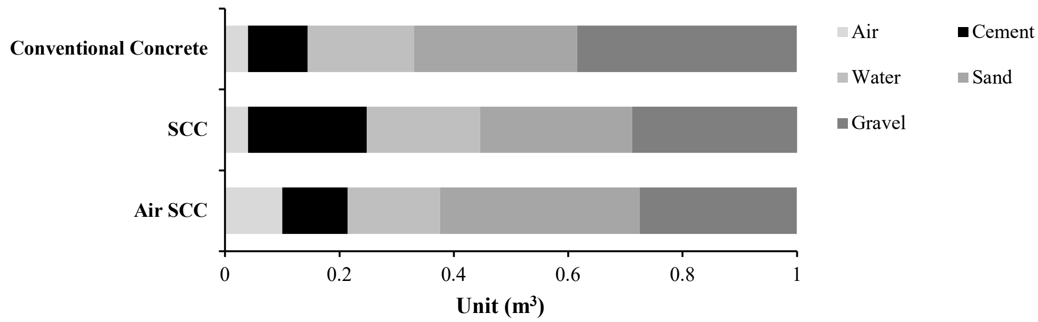

Figure 1 Proportions of materials used for producing each type of concrete.

The aim of this research is to maintain the designed air content in Air-SCC which can be reduced during transportation by increasing fine bubbles. Moreover, most of the previous research have been conducted in laboratory. The reported results should be verified with an industrial scale experiment in order to present the practicability of Air-SCC. The current study involved investigating the effect of the bubble-size distribution on the stability of the entrained air in Air-SCC with full-scale mixing. The experiments were conducted in a concrete factory in Kochi prefecture, Japan. The effects were clarified based on the mixing procedure, mixing time and type of superplasticizer.

2. Materials and methods

2.1 Materials used

The ingredients used to produce the Air-SCC in this research are commonly used in Japan. The fundamental properties of all ingredients are shown in Table 1. Ordinary Portland cement was used as the cementitious material (C). Tap water (W) supplied to the laboratory was used and the aggregate was natural limestone. The limestone was crushed to a size smaller than 4.75 mm in diameter and used as fine aggregate (s), whereas crushed limestone larger than 4.75 mm in diameter was used as coarse aggregate (G). The size of the coarse aggregate was in the range 5-20 mm. Two types of high-ranging water-reducer were used as superplasticizers (SP). One was conventional polycarboxylic ether based (PCE, SP1) and the other was also a PCE type but with retarder added (SP2). The air-entraining agent was long-chain alkylcarboxylate-based (AE) which was effective for entraining bubbles in concrete.

Table 1 Properties of ingredients used for air-enhanced self-compacting concrete.

Ingredient	Property
Cement (C)	Ordinary Portland cement (3.15 g/cm^3)
Water (W)	Tap water supplied to university (1.00 g/cm^3)
Fine aggregate (S)	Crushed limestone sand (2.68 g/cm^3, F.M. 2.96)
Coarse aggregate (G)	Crushed limestone size of 5-20 mm. (2.65 g/cm^3)
Superplasticizer (SP1)	Conventional polycarboxylic ether based
Superplasticizer (SP2)	Polycarboxylic ether-based blended with retarder
Air-entraining agent (AE)	Long-chain alkylcarboxylate-based anionic surface-active and non-ionic surface-active agent (AE: water concentration is 1:99)

2.2 Mixture proportions of air-SCC

In this work, only one mixture of Air-SCC was considered. However, the dosage of superplasticizer was slightly different according to the target flow diameter of 550-700 mm. Mixtures using SP1 needed a dosage of

1.0% of cement by weight, while mixtures using SP2 needed 1.1% of cement by weight. The proportions of the mixture are shown in Table 2.

Table 2 Mixture proportions of tested air-enhanced self-compacting concrete for 1 m^3.

Amount of ingredient (kg/m^3 of concrete volume)						Target air content (%)
Cement	Water	Fine aggregate	Coarse aggregate	Superplasticizer	Air-entraining agent	
369	166	922	729	3.69-4.06	0.554	10

2.3 Mixing procedures

Two mixing procedures were investigated in this study. The first was the conventional procedure for which all ingredients were mixed for 90 sec. However, the mixing time was prolonged to 180 sec to produce more fine bubbles (Method A) [17-18,22], shown in Figure 2A. The second mixing procedure, called the water-dividing method, was used to increase volume of fine bubbles [16-19,23]. The water and superplasticizer were mixed and then separated into two portions. The first portion was mixed with cement, fine aggregate, and coarse aggregate for 90 sec. The last portion was added with air-entraining agent and mixed for 90 sec. Prolonging the mixing time after adding the air-entraining agent from 90 sec to 180 sec was also considered for entraining more fine bubbles. The water-dividing method (Method B) is shown in Figure 2B.

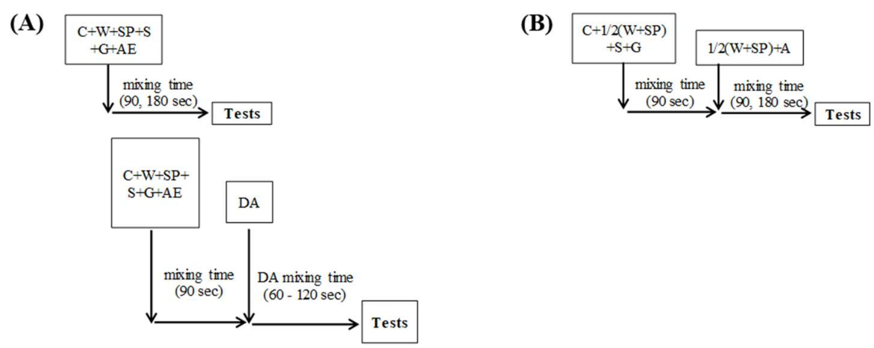

Figure 2 Concrete mixing procedures: (A) method A, (B) method B.

2.4 Parameters studied

All the parameters investigated in this research are listed in Table 3. The air-entraining agent dosage was constant at 0.15% of cement weight. The different mixing procedure, including a longer mixing time, were used to entrain more fine bubbles in the concrete. The mix codes for all mixtures consisted of three labels. The first label indicated the type of superplasticizer as SP1 or SP2. The second label indicated the mixing method as A or B. The third label indicated the mixing time after adding the air-entraining agent. For example, mix 2A180 used SP1 and was mixed using method A for 180 sec.

Table 3 Parameters studied for each mixture.

Mix	SP type	SP dosage (%C)	AE dosage (%C)	Mixing method	Mixing time for AE
1A90	1	1.0	0.15	A	90
1B90	1	1.0	0.15	B	90
2A90	2	1.1	0.15	A	90
2A180	2	1.1	0.15	A	180
2B90	2	1.1	0.15	B	90
2B180	2	1.1	0.15	B	180

2.5 Test program

All tests in this research included air measurement by weight and using the air void analyzer (AVA), a flowability test, a viscosity test, and bubble-size distribution measurement. All tests were conducted at Kochi Concrete Service, located in Kochi city, Japan. The concrete mixtures were made up in volumes of 1 m^3 and then loaded into a cement mixer truck. Each test began immediately after the concrete truck had arrived in the examination area. First, the air content was measured by weight, then concrete in a container was sieved to separate coarse aggregate from mortar which was prepared for bubble-size distribution measurement using the AVA. Flowability and viscosity tests followed, respectively. After 1 h, the concrete mixture was re-mixed in the truck for 30 sec and the tests were repeated. The sequence of testing is shown in Figure 3.

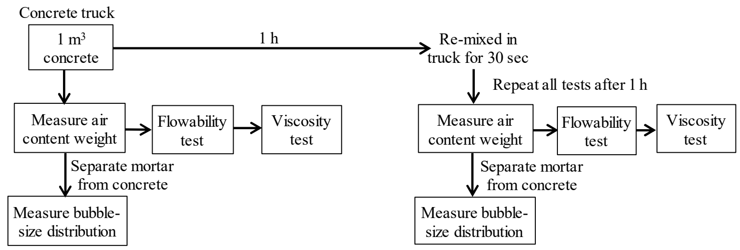

Figure 3 Test sequencing.

2.5.1 Measurement of air content

Measurement of the air content in each concrete sample involved calculating the materials used for 5 liters and comparing them to the measured weight. The air content was also obtained from the bubble-size distribution using the AVA; however, these latter values were generally lower than that obtained based on the weight. It was assumed that the air lost occurred during the sample preparation for the AVA test.

2.5.2 Standard cone flowability test

Slump flow represents the workability of self-compacting concrete which can be evaluated using a standard cone. To check for desirable flowability, the slump flow diameter-based on diameter (D1 + D2) / 2, where two diameter measurements (D1 and D2) are taken perpendicular to each other-is recommended to be in the range 550-700 mm, as shown in Figure 4 A self-compacting concrete with a satisfactory value possess low risk to segregation and high flowability.

2.5.3 Viscosity test using standard V-funnel

The viscosity of concrete was evaluated based on the standard V-funnel test, as shown in Figure 4B. Concrete was poured into a V-funnel and then released through the apparatus. The time taken from when the concrete was released until the observer noticed light from the tip of V-funnel was recorded. The measured time represents the viscosity of the concrete. The V-funnel time is recommended to be in range 4-20 sec to obtain concrete with high workability and low risk of segregation [1].

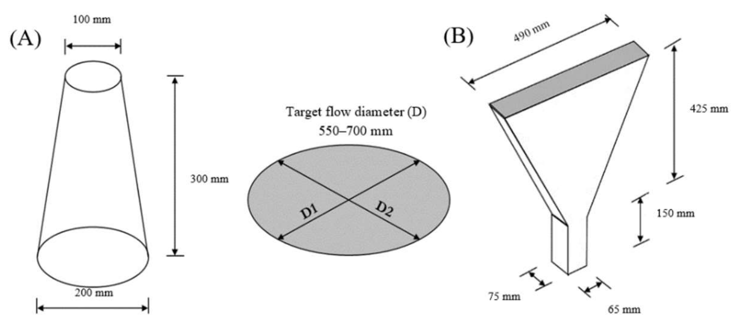

Figure 4 (A) Standard cone for testing flowability and (B) V-funnel for testing viscosity of concrete.

2.5.4 Measurement of bubble-size distribution in concrete

The AVA was used to measure the bubble-size distribution in the fresh mortar. A mortar sample was sieved from the concrete after measuring its air content by weight. Only 20 cm^3 of mortar was prepared and poured into a syringe. The AVA system consisted of a water tank, riser column and a buoyancy pan. First, the syringe containing the prepared mortar was set at the bottom of the riser column; then, water was poured in until it reached the top of the riser column. Glycerin was gently poured to the bottom of the riser column to break up the bubbles floating; then, the buoyancy pan was placed on the water surface to measure the size and total volume of the air bubbles. Once all parts were ready, measurement started with the stirring mortar for 1 min to release bubbles from the mortar, as shown in Figure 5. All the bubbles floated through the glycerin at different speeds according to the bubble size. The larger bubbles floated more rapidly than the smaller ones due to the former having a higher buoyancy force. The test was run until the buoyancy pan did not contain any bubbles. The size and total volume of bubbles in the mortar sample measured by buoyancy pan were recorded using the computer connected to the system to provide images of the bubble-size distribution.

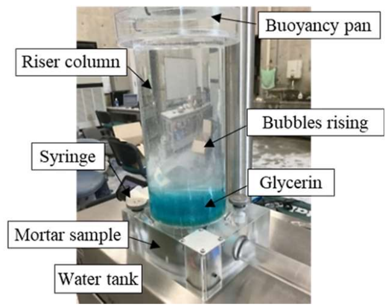

Figure 5 Measurement of bubble-size distribution using an air void analyzer.

3. Results and discussion

3.1 Reduction of air content in concrete

All Air-SCC mixtures were expected to contain an initial target air content of approximately 10%. The air contents measured by weight of all mixtures are shown in Figure 6. The initial contents were in the range 9.2-11.0%. Reductions in air content were observed in all mixtures, excepted Mix 1B90 for which the measured air content was maintained at 11.0%, although 1 h had passed. The loss of air bubbles was caused by them floating to the surface of the mixture due to the buoyancy force and then dissipating as they coalesced [17-19]. In addition, air bubbles could have disappeared during the re-mixing for 1 min in the cement truck prior to testing. However, there were possibly re-entrained bubbles in the re-mixing process as well if the air-entraining agent was still active [17]. No increase in the air content was recorded which meant that the volume of re-entrained bubbles was lower than that of the bubbles disappearing, resulting in a reduction in the overall air content in 1 h.

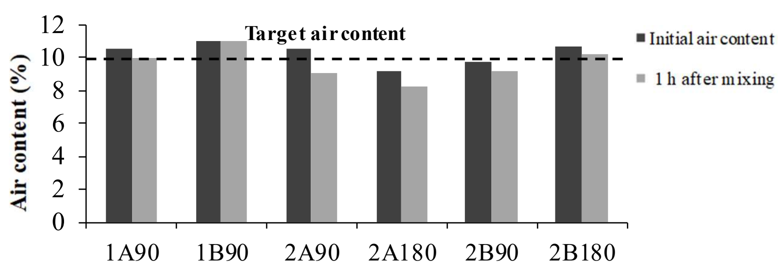

Figure 6 Reduction of air content in concrete after 1 h (measured by weight).

3.2 Size distribution of entrained bubbles in concrete

The results obtained from the AVA included bubble-size distribution and the automatically calculated specific surface area of bubbles (α). Figure 7 A-F illustrates the bubble-size distributions of the entrained air in Mixes 1A90, 1B90, 2A90, 2A180, 2B90, and 2B90, respectively. The air contents measured using the AVA were lower than the measurements by weight because of air loss during the sample preparation for the AVA test. Those lost bubbles were assumed to be large bubbles with diameter sizes greater than 1,000 µm (D>1,000 µm) based on the assumption that large bubbles were easily dissipated because of the high buoyancy force and the low inside pressure [22,23]. Therefore, the different measured air contents were added to the diameter range of 1,000-2,000 µm of the AVA results as applied by previous researchers [22,23].

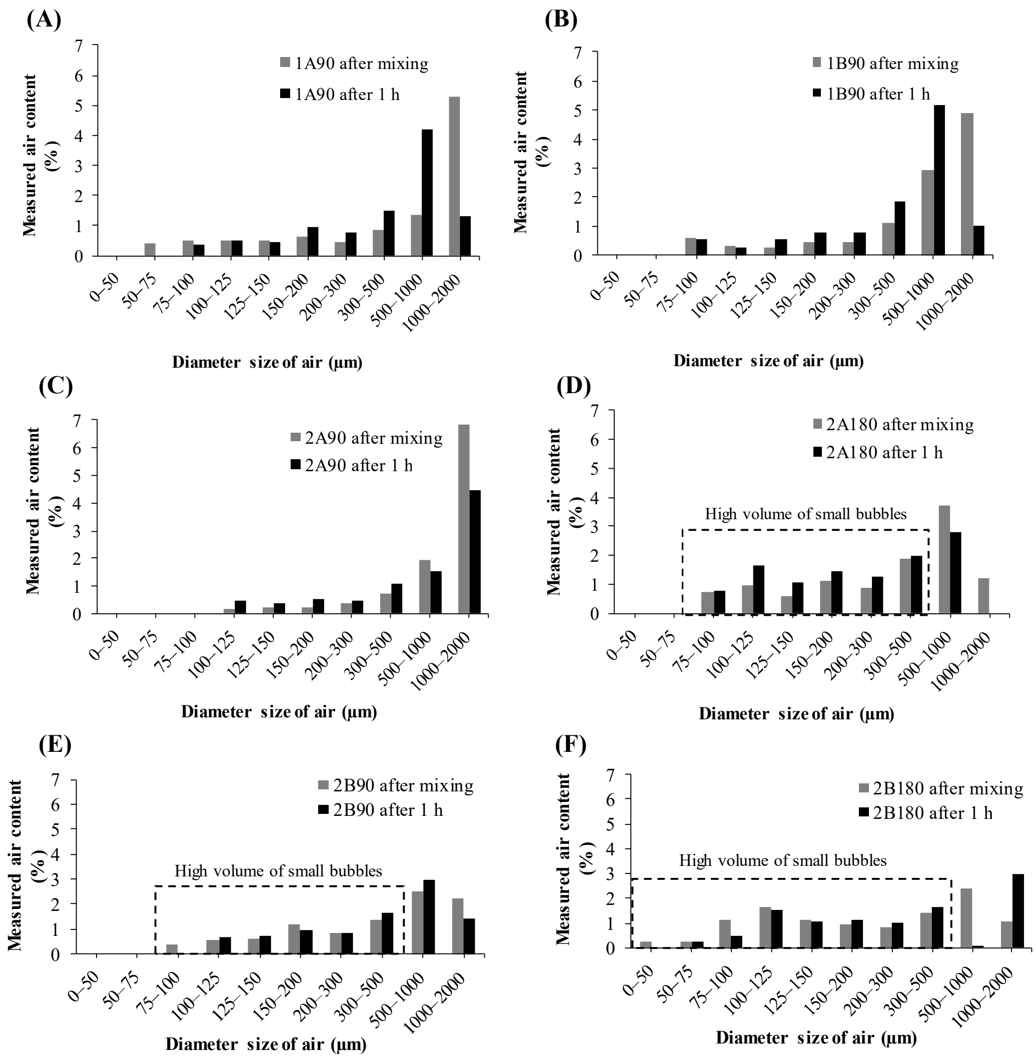

Figure 7 Bubble-size distributions of different concrete mixes: (A) 1A90, (B) 1B90, (C) 2A90, (D) 2A180, (E) 2B90, (F) 2B90.

Mixes 2A180, 2B90, and 2B180 produced significantly higher numbers of small bubbles with diameters smaller than 500 μm than Mixes 1A90, 1B90, and 2A90. Small bubbles were effectively entrained by the water-dividing method (Method B) [16] and by prolonging the mixing time [18,19]. The size of entrained bubbles related to internal friction of mixture during mixing [16]. Small bubbles were effectively entrained by water-diving method and prolonging mixing time which reduced internal friction prior to adding air-entraining agent. However, water-dividing mixing had no significant effect on entraining small bubbles in concrete using conventional superplasticizer as was evident in the comparison between Mix 1A90 and Mix 1B90 because one-half of the water and superplasticizer did not provide suitable conditions for concrete before adding the other half of the water with the air-entraining agent [16]. In contrast, the one-half water and superplasticizer in the concrete mixture using SP2 (Mix 2A90) provided suitable conditions for entraining small bubbles. This might have been caused by the retarder blended in SP2. The conditions suitable for entraining small bubbles might include uniformity of the mixture and workability as reported by Attachayawuth A, et al. [16]

3.3 Adjustment of specific surface area of bubbles

The specific surface area (α) of the entrained bubble can be represented using a relationship between the total surface area and total air volume and the original specific surface areas were calculated using the air content and bubble-size distribution measured using the AVA. Assuming the difference in air contents between measuring by weight and using the AVA was added to the bubble diameter range 1,000-2,000 µm, the specific surface areas were re-calculated and defined as the adjusted specific surface area (α_{adj}). The value of α_{adj} represented the fineness of air bubbles in concrete with the air content measured by weight. The parameters used to determine the adjusted specific surface area are provided in Table 4.

Comparisons between the α and α_{adj} values of the bubbles in all mixtures after mixing are shown in Figure 8. The α_{adj} values of Mixes 1A90, 1B90, and 2A90 were much lower than their α values due to their low volumes of small bubbles (D≤500 µm) maintained in the concrete, as discussed in section 4.5. There was a high volume of large bubbles that could escape, resulting in much lower α_{adj} values compared to the α values. The three other Mixes (2A180, 2B90, 2B90) containing high volumes of small bubbles had slight reductions in α_{adj} because the portion of large bubbles that might escape was low.

Table 4 Adjusted specific surface area of bubbles.

Mix	Air content by weight (%)	Air content by AVA (%)	Air_{weight} - Air_{AVA} (%)	Specific surface area of bubbles, α (mm^2/mm^3)	Adjusted specific surface area of bubbles, α_{adj} (mm^2/mm^3)
1A90	10.5	5.2	5.3	34.3	19.0
1A90 (1 h after)	10.0	9.9	0.1	19.4	19.1
1B90	11.0	6.1	4.9	22.0	14.0
1B90 (1 h after)	11.0	10.0	1.0	19.2	17.8
2A90	10.5	5.1	5.4	13.3	8.5
2A90 (1 h after)	9.0	4.6	4.4	22.2	13.3
2A180	9.2	11.1	-1.9	22.5	22.5
2A180 (1 h after)	8.2	11.0	-2.8	29.0	29.0
2B90	9.7	8.8	0.9	21.8	20.1
2B90 (1 h after)	9.2	9.0	0.2	19.2	18.9
2B180	11.0	10.4	0.6	37.8	35.9
2B180 (1 h after)	10.2	7.6	2.6	36.7	28.3

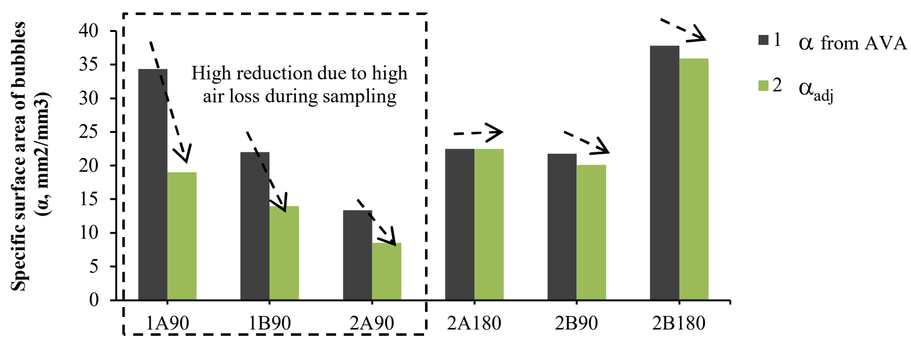

Figure 8 Adjusted value of specific surface area of bubbles.

3.4 Reduction in different measured air contents due to specific surface area of bubbles

As it was assumed that the lost bubbles during the preparation process using the AVA were in the bubble diameter range 1,000-2,000 µm and this affected the specific surface area of the bubbles, the relationship between the different measured air contents and the adjusted specific surface area (α_{adj}) is shown in Figure 9. The reduction in the different values meant a reduction in bubbles in the diameter range 1,000-2,000 µm. The loss of those bubbles reduced according to the increase in α_{adj} because once the average size of the bubbles was small (high α_{adj}), stabilization of bubbles became high, resulting in a low amount of air being lost. On the other hand, entrained bubbles with a low α_{adj} faced a high reduction rate of air lost, plotted as the left-most point in Figure 9 where α_{adj} = 8.5 mm^2/mm^3 and air lost = 5.4%. However, the rate of reduction in air lost depended on various factors such as flowability, viscosity, and human error during sampling. Thus, there are two apparent trends in Figure 9.

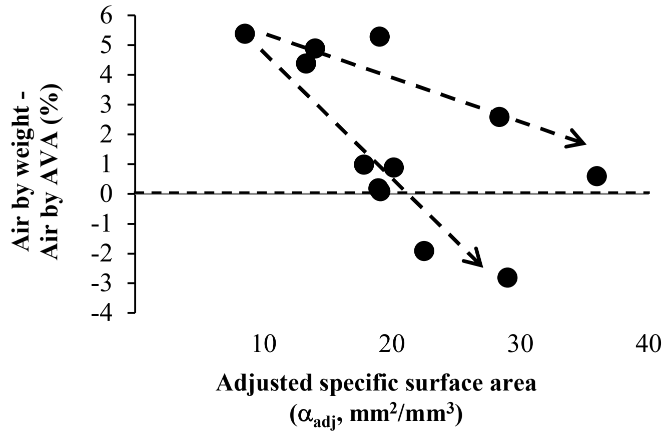

Figure 9 Comparison of air content measured by weight and using AVA.

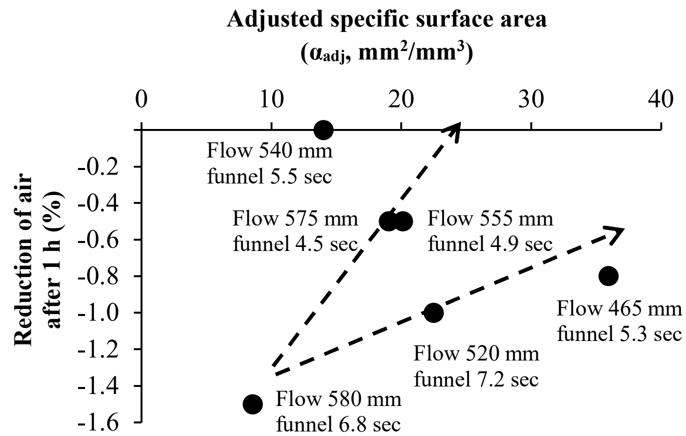

Figure 10 Reduction in air content in 1 h with respect to adjusted specific area of bubbles.

3.5 Mitigation of air lost in 1 h due to specific surface area of bubbles

Figure. 10 shows the reduction in the air content in 1 h for all mixes with respect to the adjusted specific area of bubbles (α_{adj}). The reduction in the air content was in accordance with the increased specific surface area of bubbles (α_{adj}). Small bubbles (high α) were retained in mixtures in preference to large bubbles (low α). Mix 1A90 with α_{adj} = 8.5 mm^2/mm^3 had a 1.5% reduction in the air content in 1 h which could affect self-compactability, freeze-thaw resistance and shrinkage [16]. The two trends in the reduction rate can be seen in Figure 10. Although large bubbles escaped easily, this was dependent on the mixture conditions including flowability and viscosity. There was little reduced air content (approximately 0.5%) in mixtures with suitable flowability (flow diameter of 550-700 mm), viscosity (V-funnel time over 4 s) and α_{adj} of approximately 20 mm^2/mm^3, as shown in Figure 10, while mixtures with α_{adj} values of 22.5 and 35.9 had expected low reductions in the air content (1.0% and 0.8%, respectively), had flow diameters of 465 and 520 mm, respectively, and were not in the target range. No reduction in 1 h with α_{adj} = 17.8 mm^2/mm^3 and flow diameter = 540 mm. However, increasing α_{adj} resulted in a reduction in the air that escaped in 1 h. The effectiveness of the reduction strongly depended on suitable conditions of mixtures that involved flowability and viscosity. Bubbles could move easier in highly flowable concrete (high flow diameter) due to high deformability of the matrix.

4. Conclusion

The air size distributions and the specific surface areas of bubbles were measured in concrete mixtures using various mixing times and mixing procedures at a concrete plant. The results showed that the overall effects of the parameter studied on the stability of Air-SCC with respect to air size distribution were: 1) Entraining small bubbles in Air-SCC by water-diving method and prolonging mixing time with full-scale experiment has been succeeded. Those procedures could be applied to concrete industry for improving air stability in concrete, 2) Small, entrained bubbles with diameter sizes smaller than 500 μm were effectively produced by the water-dividing method combined and 180 sec mixing for the simple method with superplasticizer blended with retarder. This technique was not effective for mixtures using the conventional superplasticizer. Concrete users are capable of maintaining the designed air content in mixtures using this technique to effectively prevent air lost during transportation and maintain durability of concrete, and 3) The specific surface area of bubbles (α) played an important role in maintaining the stability of the air bubbles in 1 h. Stability of air was clearly improved by increasing the specific surface area of the bubbles by increasing the volume of the small bubbles. However, it could be improved more in suitable mixtures with flow diameters in the range 550-700 mm and a V-funnel time over 4 sec.

The chemical admixtures used in this work were only high-range water-reducer. A lot of chemical admixtures have been developed for many purposed. New type admixtures or combined materials affecting the entrainment of bubbles is interesting. The future work should be focused on new type of chemical admixtures and attempt to use this concrete for real construction project.

5. Acknowledgements

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