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*Article*

# Effects of Air-Entraining Agent, Defoaming Agent and Mixing Time on Characteristic of Entrained Bubbles in Air-Enhanced Self-Compacting Concrete Mixed at Concrete Plant

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**Abstract.** This paper presents a full-scale experimental study on the use of an air-entraining agent and defoaming agent combined with mixing time to entrain small-sized air bubbles in air-enhanced self-compacting concrete (Air-SCC). The fresh properties (flowability and V-funnel time) were determined. An air void analyzer (AVA) was used to measure the diameter size of bubbles entrained in the fresh stage. The dosages of both air-entraining agent (AE) and defoaming agent with different mixing times were investigated for their effects on the bubble size distribution. The results indicated that the portion of small bubbles with a diameter size less than 1,000 μm could be increased by increasing the AE dosage. Furthermore, prolonging the mixing time notably increased the volume of small bubbles, while producing no substantial change in the volume of large bubbles. Defoaming agent eliminated both small and large bubbles; however, small bubbles could be entrained concurrently with a reduction in large bubbles by increasing the dosage of defoaming agent or prolonging the mixing time after adding it. All investigated results confirmed that the effects of various parameters on characteristic of entrained air in concrete with full scale mixing are in agreement with the results of concrete investigated in laboratory by many researchers. These findings are beneficial for designing mixtures of Air-SCC containing high volumes of small bubbles that improve the self-compactability and freeze-thaw resistance of concrete.

**Keywords:** Air-enhanced self-compacting concrete, entrained air, air size distribution, air-entraining agent, defoaming agent.

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## 1. Introduction

Self-compacting concrete (SCC) has been developed since 1988 to improve the reliability and durability of concrete structures [1]. The design of mix proportion of self-compacting could be optimized with respect to early age strength up to 120 MPa. [2] It has been called high-performance concrete because it has high strength and high flowability [3]. This type of concrete can be compacted by its own weight without vibration due to the presence of a superplasticizer [4]. High-range water-reducing admixture is necessary to create a repulsive force between the cement particles [5]. Polycarboxylate (PC) base superplasticizer has been used widely in the past decade to effectively promote self-compactability of SCC. The PC type has been developed based on polymer chains and structures with its chemical composition to the rheological properties of the concrete [6-10]. There are many applications of self-compacting concrete have been developed in the past 20 years for various purposes. Various research projects have been reported globally to produce concrete with high flowability such as self-compacting concrete with the addition of various types of fiber to improve mechanical strengths [11-24] and the use of fly ash as a partial cement replacement to reduce the cement content and the enhance flowability of SCC [25-35]. Recently, the very interesting application of self-compacting concrete or mortar is the use of flowable concrete for modern construction by 3D printing [36-37]. This shows the useful and popularity of self-compacting concrete that still being developed in construction industry. Researchers have investigated various factors to improve self-compactability of concrete such as using plastic beads as fine aggregate replacement, entraining air bubbles in concrete mixtures [38] etc. Self-compactability were improved in some cases because it depends on both materials used and concrete mixtures including chemical admixtures and mixing procedures.

Recently, air-enhanced self-compacting concrete (Air-SCC) was invented by entraining approximately 10% fine bubbles [38]. The volumes of the fundamental ingredients used for the mix proportions of Air-SCC compared to conventional concrete and conventional self-compacting concrete are shown in Fig. 1. The cement content of Air-SCC is considerably lower than that of conventional SCC which results in lower heat being produced from the hydration reaction. Furthermore, the volume of fine aggregate could be increased to approximately 20% with similar self-compactability. Air bubbles with diameters smaller than 500 μm were considered effective for self-compactability enhancement. Those bubbles were also effective for stability improvement of bubbles in concrete. [39-40]. The volume of small air bubbles in concrete could be increased by using a specific mixing procedure called the water dividing method [38, 41-42]. In addition, defoaming agent was used based on the assumption that large bubbles would be eliminated during mixing by destabilizing the walls of air bubbles [43-45]. The results obtained agreed with the assumption [46-47]. However, the verification of the results with a real scale concrete experiment is necessary. Therefore, the authors and research team have focused on the practicability of air-enhanced self-compacting concrete for future application in concrete industry. Eventually, the advantage on self-compactability by fine entrained bubbles will be maximized with chemical admixtures and mixing procedures.

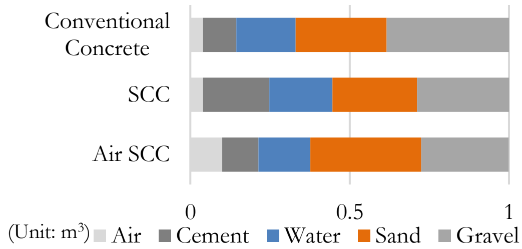



Fig. 1. Volume of materials to make 1 m$^3$ of concrete.

The aim of the current study was to verify the results from previous researchers with full scale mixing at a concrete plant to confirm the practicability of Air-SCC. More importantly, concrete user or designer can apply the results to maximize self-compactability and freezing-thawing resistance by using air-entraining agent and defoaming agent with adjustment of mixing time. A simple suggestion for improving self-compactability and freezing-thawing resistance with respect to air-entraining, defoaming agent and mixing time will be presented. The experiments were conducted at a concrete plant in Kochi City, Japan. The effects were clarified of air-entraining, defoaming agent and mixing time on the bubble size distribution in concrete.

## 2. Materials Used and Mix Proportions

### 2.1. Material Used

All the materials used in this research were produced in Japan. Ordinary Portland cement was used as the cementitious material. The fine aggregate (S) was crushed limestone sand with fineness modulus of 2.96. Crushed limestone (5–20 mm in size) was used as the coarse aggregate (G). Polycarboxylic base blended with a viscosity agent was used as superplasticizer (SP) and high-range water-reducing agent. This type of superplasticizer works with main carbon chain carboxylate groups as the electro-repulsive force and polyethylene oxide side chain provide steric hindrance [7]. The air-entraining agent (AE) was an alkylcarboxylate-based anionic surfactant and the defoaming agent (DA) was polyalkylene glycol derivative. The fundamental properties of all materials used are shown in Table 1.

Table 1. Properties of materials used in air-enhanced self-compacting concrete.

| Material | Property |
|---|---|
| Cement (C) | Ordinary Portland cement (3.15 g/cm$^3$) |
| Water (W) | General 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 (5–20 mm size; 2.65 g/cm$^3$) |
| Superplasticizer (SP) | Polycarboxylic base blended with viscosity agent |
| Air-entraining agent (AE) | Long-chain alkylcarboxylate-based anionic surface-active and non-ionic surface-active agent (AE:water concentration = 1:99) |
| Defoaming agent (DA) | Polyalkylene glycol derivative |

### 2.2. Mix Proportion of Concrete

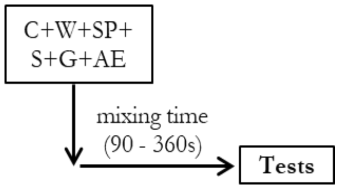
The concrete mixture was designed as air-enhanced Self-Compacting Concrete (Air-SCC) with an air content of approximately 10%. Table 2 shows the quantities of the main ingredients by weight to produce 1 m$^3$ of Air-SCC. The dosage of superplasticizer added was approximately 3.69–4.80 kg to enhance the flowability of concrete with a flow diameter in the range 550–700 mm. Air-entraining agent (AE) was used in the range 0.369–0.554 kg to produce a target air content of 10%. For mixtures where a defoaming agent (DA) was used to eliminate coarse air bubbles, 0.055–0.222 kg of DA was added.

Table 2. Mix proportions of air-enhanced self-compacting concrete to make 1 m$^3$.

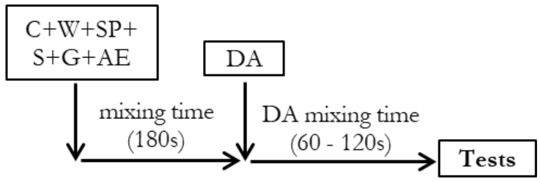
| Concrete volume (kg/m$^3$) | | | | Target air content |
|---|---|---|---|---|
| **Cement** | **Water** | **Fine aggregate** | **Coarse aggregate** | |
| 369 | 166 | 922 | 729 | 10% |

### 2.3. Mixing Procedures

The concrete mixing and tests were conducted at Kochi Concrete Service in Kochi prefecture, Japan. All mixtures were made up to 1 m$^3$ to verify the practical use of Air-SCC based on full scale mixing. The mixing steps for Air-SCC started with mixing the cement, water, superplasticizer, fine aggregate, coarse aggregate, and air-entraining agent. The time for mixing these ingredients for the concrete mixtures without defoaming agent was in the range 90–360 s, as shown in Fig. 2(a). The mixing steps for Air-SCC with defoaming agent are shown in Fig. 2(b). The mixing time after adding all ingredients except DA was fixed at 180 s. Then, DA was added and mixed for 60–120s and noted as the DA mixing time with all ingredients.




(a) Mixing steps of proportions without defoaming agent




(b) Mixing steps of proportions with defoaming agent

C: Cement, W: Water, SP: Superplasticizer, G: Gravel
S: Sand, AE: Air-entraining agent, DA: Defoaming agent

Fig. 2. Mixing steps for concrete tested.

### 2.4. Parameters Studied

This work focused on parameters affecting the initial characteristics of the entrained bubbles, namely the dosage of air-entraining agent, the dosage of defoaming agent and its mixing time. The parameters considered for the 10 mixtures tested are provided in Table 3. The effect of SP dosage affecting the flow diameter of the concrete and the characteristics of the entrained bubbles were obtained by comparing the results of Mixes No. 1 and No. 2. Comparing the test results of Mixes No. 3 and No. 6 obtained the effects of the AE dosage. The effects of mixing time on the entrained air could be explained by analyzing the results of Mixes No. 4 –6, and the effects of the DA mixing time were based on the results of Mixes No. 8 and No. 10. The test results of Mixes No. 2 and No. 7–9 showed the effects of the DA dosage.

Table 3. Parameters studied in this research.

| Mix No. | SP dosage | AE dosage | Mixing Time | DA dosage | DA Mixing Time |
|---|---|---|---|---|---|
| 1 | 1.0%C | 0.15%C | 180 s | - | - |
| 2 | 1.2%C | 0.15%C | 180 s | - | - |
| 3 | 1.3%C | 0.15%C | 360 s | - | - |
| 4 | 1.3%C | 0.10%C | 90 s | - | - |
| 5 | 1.3%C | 0.10%C | 180 s | - | - |
| 6 | 1.3%C | 0.10%C | 360 s | - | - |
| 7 | 1.2%C | 0.15%C | 180 s | 0.015%C | 60 s |
| 8 | 1.2%C | 0.15%C | 180 s | 0.030%C | 60 s |
| 9 | 1.2%C | 0.15%C | 180 s | 0.060%C | 60 s |
| 10 | 1.2%C | 0.15%C | 180 s | 0.030%C | 120 s |

## 3. Experimental Programs

The experimental programs involved a flowability test, V-funnel test, and measurement of air diameter size distribution. The three tests were conducted in the laboratory at the concrete plant.

### 3.1. Measurement of Air Content

The first test after mixing the concrete was air content measurement that was measured in mixtures using the pressure method according to ASTM C231 [48]. Then, the weight of each concrete sample in the container was measured and compared with the calculated weight of materials used in a unit volume of sample to recheck the air content by weight. The last measured air content was simultaneously obtained with air size distribution using the AVA. Therefore, three air content measurements obtained from different three methods were reported in this research.

### 3.2. Flowability Test

After measuring the air content, each concrete sample was poured into a standard cone without any compaction and the cone was gently lifted. The flow diameter representing the flowability of the mixture was measured after the mixture had stabilized. The diameter of the concrete was measured in two perpendicular directions. The target flow diameter was 550–700 mm. The size of the standard cone, and the measurement of flow diameter are illustrated in Fig. 3.

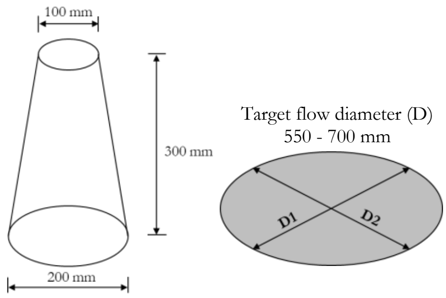



Fig. 3. Measurement of air diameter using air void analyzer.

### 3.3. Test of V-Funnel Time

The V-funnel test was performed immediately after the flowability test. The mixture was poured into a standard V-funnel, as shown in Fig. 4. Then, the time that concrete took to pass through the funnel was measured. The measured time was recorded from when the mixture was released until the observer noticed a hole at the tip of the V-funnel. This test was performed to evaluate the mixture viscosity. The recommended funnel time is 4–20s. Generally, self-compacting concrete with a recommended time would possess high workability without segregation.

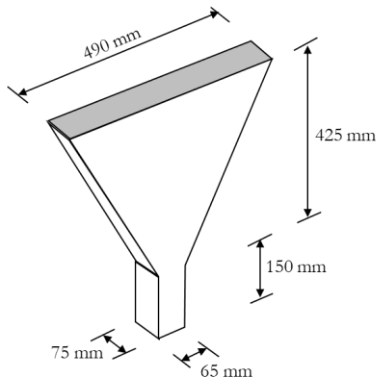



Fig. 4. Standard size of V-funnel for concrete.

### 3.4. Measurement of Air Size Distribution

The core test of this research was the measurement of air size distribution. An AVA was used to measure bubble diameters and the air content in a mortar sample. The mortar sample was separated from gravel by sieving a concrete sample after all the tests in 3.1, 3.2 and 3.3 had been completed. Only 20 $cm^3$ of mortar sample was poured into a syringe and inserted in the bottom of the riser column. To the released liquid, glycerin was added to the top of mortar sample to slow the floating speed of the air bubbles. At the start of the test, the mortar sample was stirred for 1 minute to separate all bubbles from the mortar. The air bubbles floated through the glycerin and stopped at the buoyancy pan that was connected to the weight scale for calculating bubble diameter. Larger bubbles were first observed because of their higer buoyancy force. The test was run until no more bubbles were noticed or only very small bubbles remained that could not be detected by AVA.

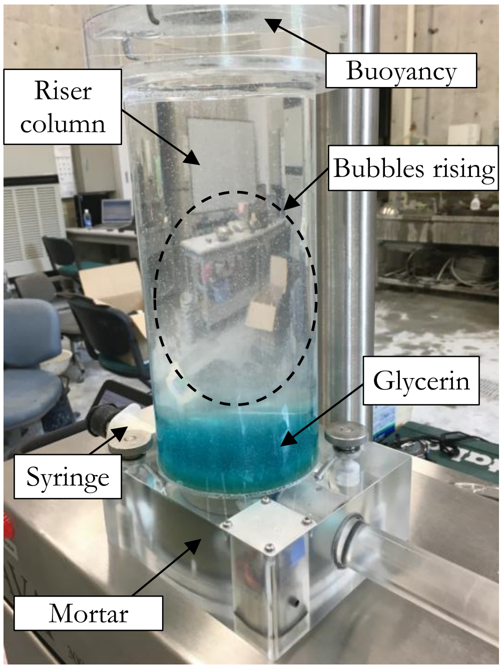



Fig. 5. Measurement of air diameter using air void analyzer.

## 4. Results and Discussion

The air content measured using the three methods and the tested fresh properties including flow diameter and V-funnel time of 10 Air-SCC mixtures are tabulated in Table 4.

Table 4. Results of tested fresh properties.

| Mix No. | Measured Air Content (%) | | | Flow Diameter (mm) | V-Funnel Time (s) |
|---|---|---|---|---|---|
| | by pressure | by weight | by AVA | | |
| 1 | 10.5 | 10.7 | 5.32 | 520 | 5.91 |
| 2 | 11.2 | 11.5 | 6.30 | 580 | 6.10 |
| 3 | 10.8 | 11.4 | 9.52 | 615 | 4.38 |
| 4 | 6.2 | 5.5 | 3.36 | 550 | 7.84 |
| 5 | 11.0 | 8.7 | 7.07 | 615 | 6.19 |
| 6 | 11.8 | 10.6 | 9.17 | 600 | 5.90 |
| 7 | 8.8 | 9.1 | 3.43 | 620 | 4.28 |
| 8 | 7.6 | 7.6 | 3.43 | 630 | 5.06 |
| 9 | 7.8 | 7.9 | 3.92 | 655 | 5.16 |
| 10 | 8.6 | 8.4 | 5.04 | 680 | 4.50 |

Table 5. Diameter sizes of bubbles in all mixtures with diameter (D) smaller and larger than 1,000 μm.

| Mix No. | Total air content (%) | Air content (%) | |
|---|---|---|---|
| | | D<1,000 μm | D≥1,000 μm |
| 1 | 10.7 | 4.4 | 6.3 |
| 2 | 11.5 | 5.9 | 5.6 |
| 3 | 11.4 | 8.4 | 3.0 |
| 4 | 5.5 | 2.8 | 2.7 |
| 5 | 8.7 | 5.7 | 3.0 |
| 6 | 10.6 | 7.4 | 3.2 |
| 7 | 9.1 | 3.1 | 6.0 |
| 8 | 7.6 | 3.4 | 4.2 |
| 9 | 7.9 | 3.8 | 4.1 |
| 10 | 8.4 | 4.5 | 3.9 |

### 4.1. Initial Air Content in Concrete

The target air content was 10%, but the measured values were not identical due to combination effects, chemical admixtures and mixing procedures. The measured initial air contents of all mixtures based on the three methods are shown in Fig. 6, indicating that the air content based on the pressure and weight methods were very similar. However, the value measured using the AVA was substantially lower from the other two methods. This could be explained by the air bubbles disappearing during the sieving process to separate mortar and gravel. Mortar and air bubbles were exposed to the ambient environment during this process so that some of bubbles dissolved into the atmosphere, resulting in the noticeably lower measured air content using the AVA.

Only the air content by weight of Mix No. 4 was less than 7.0% because of insufficient mixing time. However, the air content could be increased by increasing the AE dosage as shown in Mixes No. 3 and no. 6. The air content depended on various parameters that were the focus of this work.

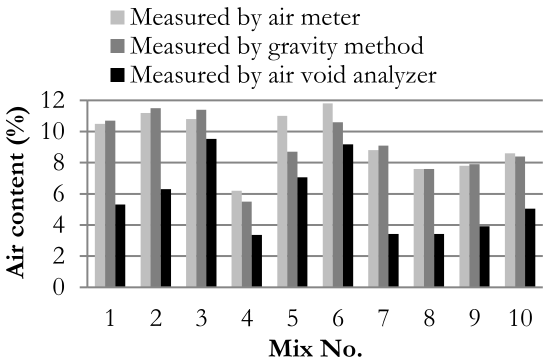



Fig. 6. Initial air content of mix proportions measured using three methods.

To analyze the bubble size distribution in concrete, the different values of air content measured by weight and AVA were determined for bubble diameters greater than 1,000 μm. Therefore, the results of the size distribution of bubbles were adjusted to determine the adjusted bubble

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size distribution. It was assumed that the larger bubbles were easily collapsed due to their low internal pressure. Furthermore, the larger bubbles could be moved more easily upward by the buoyancy force during the tests from the beginning, with the AVA test being the last. This resulted in instability of the air bubbles in the concrete during transportation and casting, as reported by [49].

### 4.2. Fresh Properties of Concrete

The fresh properties of Air-SCC in this work were flowability and V-funnel test.

#### 4.2.1. Flow Diameter

There was only one mix (Mix No. 1) for which the flow diameter was out of the target range because the amount of superplasticizer was 1.0% of cement by weight which was insufficient to reach the 550 mm flow diameter. However, this could be simply increased by adding more SP or water to the cement ratio. Mixes No. 2–9 satisfied the target flow diameter range of 550–700 mm. The test results of flowability of all mixtures are shown in Fig. 7.

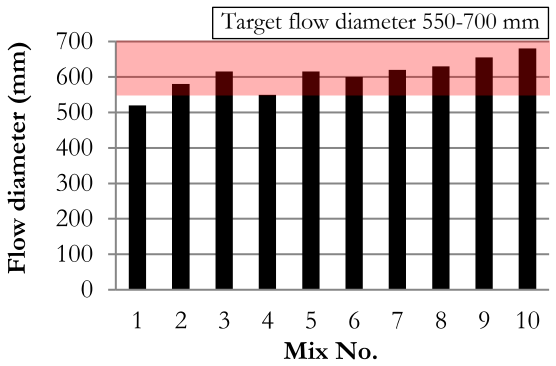



Fig. 7. Measurement of air diameter using air void analyzer, where red zone indicates target diameter range.

#### 4.2.2. V-Funnel Time

Figure 8 shows the results of V-funnel time for all the concrete mixes. The V-funnel time represents the viscosity of the concrete. The recommended time was 4–20 s for flowable concrete without segregation. The results showed that the V-funnel time for the 10 mixes was in range 4–8 s, so all mixtures were satisfactory and could be considered as applicable Air-SCC.

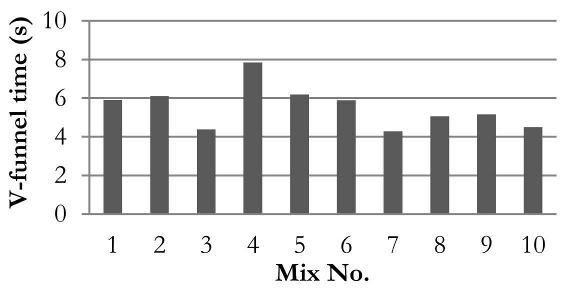
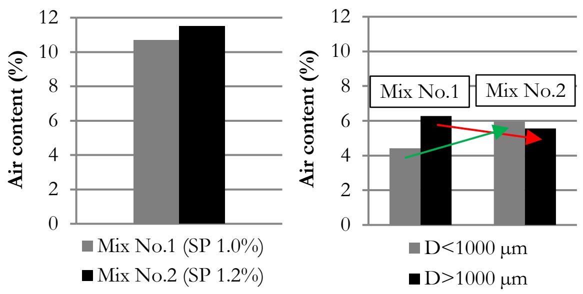



Fig. 8. Measurement of air diameter using air void analyzer.

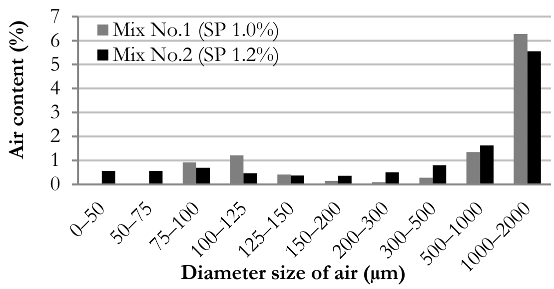
### 4.3. Effect of Dosage of Superplasticizer on Characteristic of Air Bubbles

Figure 9(a) shows the adjusted air content and proportion of small bubbles (D<1,000μm) and large bubbles (D>1,000μm) of Mixes No. 1 and no. 2. The adjusted air content increased from 10.7% to 11.5% by increasing the SP dosage from 1.0% to 1.2% It was clear that increasing the SP dosage could increase the air content. However, the increased value was for small bubbles, whereas the content of large bubbles reduced which was beneficial to the self-compactability of concrete [35].

The adjusted bubble size distribution of Mixes No. 1 and 2 are shown in Fig. 9(b). Bubble diameters of 0–75, were observed in Mix No. 2 but not in Mix No. 2. The air size distribution of Mix No. 2 seemed more balanced than for Mix No.1 due to the higher SP dosage. A small flow diameter might affect the air entrainment process, resulted in an unbalanced air size distribution.




(a) Adjusted air content of concrete, a green arrow indicates air volume increase, a red arrow indicates air volume reduction.



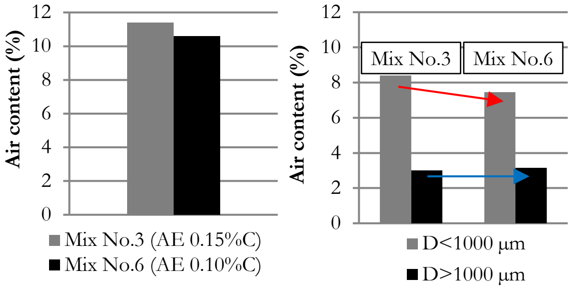

(b) Air size distribution of concrete

Fig. 9. Measured characteristic of air bubbles for variation in SP dosage.

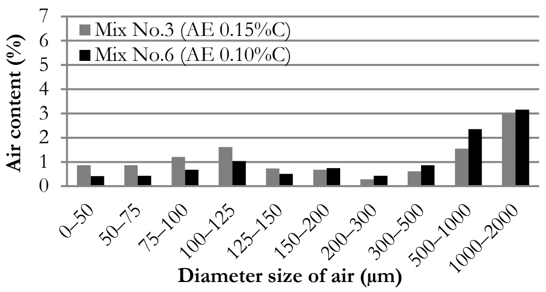
### 4.4. Effect of Dosage of Air-Entraining Agent on Characteristic of Air Bubbles

The effect of the air content by the dosage of added AE is shown in Fig. 10(a). It was found that the air content slightly reduced from 11.4% to 10.6% by reducing the AE dosage from 0.15%C to 0.10%C. However, it was notable that the reduced value was only due to the portion of small bubbles because the portion of large bubble of those two mixes were very close.

Figure 10(b) shows the similar bubble size distributions of Mixes No. 3 and No. 6. The volume of fine bubbles (D<125 µm) was higher than that of moderate bubbles (125≤D≤500 µm) and was lower than that of large bubbles (D>500 µm). Thus, slightly reducing the AE dosage had no major effect on both the air content and the pattern of bubble size distribution.




(a) Adjusted air content of concrete, a red arrow indicates air volume reduction, a blue arrow indicates similar air volume.



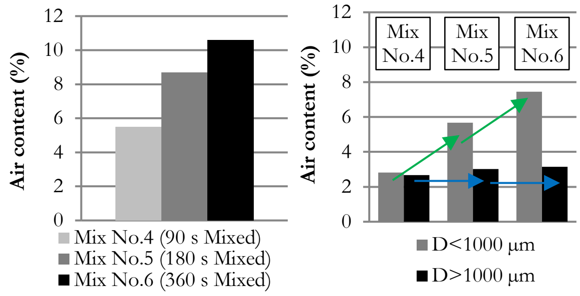

(b) Air size distribution of concrete

Fig. 10. Air size distribution of concrete for variation in AE dosage.

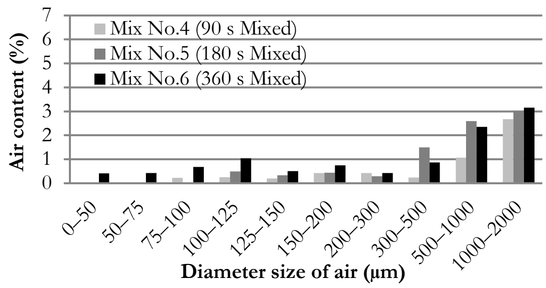
## 4.5. Effect of Mixing Time after Adding Air-Entraining Agent on Characteristic of Air Bubbles

The results of Mixes No. 4, No. 5 and No.6 could explain the effects of mixing time on the air content and characteristic of air bubbles in concrete. It was noticeable that the air content gradually increased with increasing mixing time. The air content was 5.5%, 8.7% and 10.6% for concrete mixtures mixed for 90s, 180s and 360s, respectively. The increased air content was in the portion of small bubbles with diameters less than 1,000 µm. It can be explained that the smaller bubbles were divided from the larger bubbles during mixing process, which conformed to the results reported by Nipat [42]. The volume of bubbles larger than 1000 µm slightly changed due to the volume of re-entrained bubbles might be similar to that of disappeared bubbles during mixing. Thus, increasing the mixing time could entrain a greater air content, especially as small bubbles (D<125 µm). The air content of Mixes No. 4, No. 5 and No. 6 are illustrated in Fig. 11(a).

Figure 11(b) shows the bubble size distributions of Mixes No. 4, No. 5 and No. 6, where all bubble sizes were produced by increasing the mixing time to 360 s, whereas bubbles with diameters smaller than 75 µm were not formed. In overview, the volumes of fine and moderate sized bubbles in Mix No. 6 were the greatest, followed by Mixes No.5 and No. 6, respectively. The conclusion of this part was that the mixing time played an important role in the size of the bubbles entrained during the mixing process. The volumes of fine and moderate bubbles could be increased by increasing the mixing time of the concrete.




(a) Adjusted air content of concrete, a green arrow indicates air volume increase, a blue arrow indicates similar air volume.




(b) Air size distribution of concrete

Fig. 11. Air size distribution of concrete for variation in mixing time of AE.

## 4.6. Effect of Dosage of Defoaming Agent on Characteristic of Air Bubbles

Defoaming agent (DA) was applied under the hypothesis that it would eliminate large bubbles in the concrete [43-44]. Figure 12 (a) shows the air content in concrete without DA (Mix No. 2) and with various dosages of added DA (Mixes No. 7–9) in terms of the total air content and separately for considering small and larger bubbles. The total air content reduced from 11.5% to 7.6–9.1% due to the addition of a DA dosage of 0.015–0.060%C. Increasing the DA dosage from 0.030%C to 0.060%C resulted in a slight reduction in the air content. There were similar volumes of small and large bubbles, both portions in the concrete without DA (Mix No. 2). The addition of defoaming agent of 0.015%C substantially reduced the portion of small bubbles. Nevertheless, the volume of small bubbles increased, and the volume of large bubbles decreased with an increasing dosage of DA,

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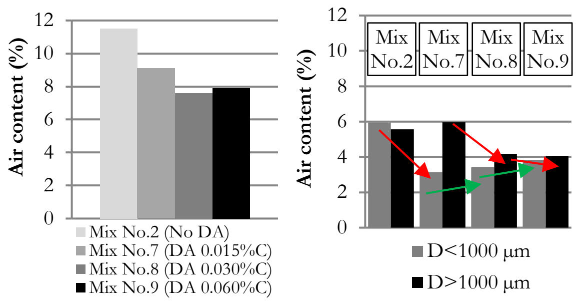
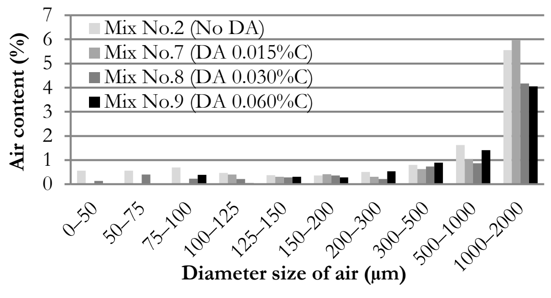
which was advantageous in terms of self-compactability improvement.

Figure 12(b) shows the bubble size distribution of Mixes No. 2, No. 7, No. 8 and No. 9. It was observed that large bubbles (D>500 μm) were reduced effectively by adding a DA dosage of more than 0.030%C. However, small air bubbles were also eliminated, especially the fine bubbles. The presence of defoaming agent seemed to reduce all sizes of bubbles but increasing its dosage resulted in higher amounts of small bubbles. The presence of defoaming agent reduced surface tension of bubbles and might destroy elasticity of the film of bubbles which resulted in significant reduction in total air content. However, the volume of small bubbles slightly increased, and the volume of large bubbles reduced due to the increase of dosage of defoaming agent. It can be explained that the large bubbles possessed larger surface area comparing to the small bubbles, thus it was easier to be eliminated or divided into small bubbles. Accordingly, the elimination of larger bubbles might affect the increase of volume of small bubbles.




(a) Adjusted air content of concrete, a green arrow indicates air volume increase, a red arrow indicates air volume reduction.



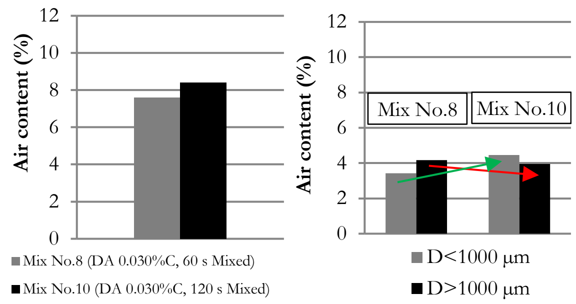

(b) Air size distribution of concrete

Fig. 12. Air size distribution of concrete for variation in DA dosage.

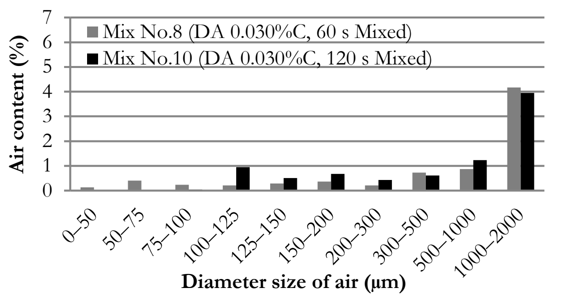
## 4.7. Effect of Mixing Time after Adding Defoaming Agent on Characteristic of Air Bubbles

The results for Mixes No. 8 and No. 10 were compared to explain the effect of the mixing time of DA on air entrainment. The total air content slightly increased from 7.6% to 8.4% by prolonging the mixing time after adding DA from 60 s to 120 s. It was possible that the increased volume was bubbles which had been re-entrained. However, the volume of small bubbles increased and the volume of large bubbles decreased, as shown in Fig. 13(a). A longer mixing time after adding DA affected both the re-entrainment of bubbles by AE and the elimination of bubbles by DA. The combined effects of AE and DA due to the longer mixing time resulted in a higher volume of small bubbles and a lower volume of large bubbles. The large bubbles were eliminated and divided during prolonging mixing time, whereas the portion of small bubbles increased due to the re-entrainment and divide of large bubbles as mentioned in 4.5 and 4.6.

Figure 13(b) shows the bubble size distribution of Mixes No. 8 and No. 10. All sizes of bubble were present in Mix No. 8 (60 s mixing time), while bubble diameters larger than 100 μm were clearly observed in Mix No. 10 (120 s mixing time). Furthermore, the volume of bubble diameters larger than 100 μm in Mix No. 10 was substantially higher than for Mix No. 8. This might have been due to the coalescence of fine bubbles and small bubbles during the longer mixing time [42].




(a) Adjusted air content of concrete, a green arrow indicates air volume increase, a red arrow indicates air volume reduction.




(b) Air size distribution of concrete

Fig. 13. Air size distribution of concrete for variation in mixing time of DA.

## 5. Conclusions

The air size distributions were measured of concrete mixtures using various mixing times and dosages of chemical admixtures at a concrete plant. The results showed that the overall effects of the parameter studied on the bubble size distribution of Air-Enhanced Self-Compacting Concrete (Air-SCC) were:

1. The practicability of using air-entraining agent and defoaming agent combined with suitable mixing time and its dosage to effectively produced small bubbles in self-compacting concrete investigated with full-scale experiment was succeeded. Engineers can apply these results to design concrete mixtures that need both high self-compactability and high freezing-thawing resistance for various purposes.

2. The volume of small bubbles increased and the volume of the large bubbles decreased when the dosage of superplasticizer was increased. Entrainment of small bubbles in higher flowable SCC was more effective and let large bubbles escape the mixture during the mixing process.

3. The total air content slightly reduced (especially the portion of small bubbles) due to a reduction in the dosage of air-entraining agent.

4. The mixing time after adding the air-entraining agent played a major role in the entrainment of air bubbles. The small bubble portion noticeably increased with increased mixing time of the air-entraining agent while the portion of large bubbles changed slightly. Re-entrainment of small bubbles and the disappearance of large bubbles occurred at the same time during longer mixing times. This can help engineers to maximize the advantages on self-compactability and freezing-thawing resistance by only adjusting mixing time with the same resources.

5. Defoaming agent mainly reduced both small and large bubbles. However, the portion of small bubbles increased together with the portion of large bubbles being reduced by increasing the dosage of defoaming agent.

6. The portion of small bubbles increased by prolonging the mixing time after adding the defoaming agent because the air-entraining agent was still working in the mixture. On the other hand, more large bubbles escaped during the longer mixing time, resulting in a reduced volume of large bubbles. This can also be applied to maximize the properties of concrete with respect to the increase of portion of small bubbles.

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## References

[1] K. Ozawa, et al., "Development of high-performance concrete based on the durability design of concrete structures," in *Proceedings of the Second East Asia and Pacific Conference on Structural Engineering and Construction (EASEC-2)*, 1989, vol. 1, pp. 445–450.

[2] D. K. Ashish and S. K. Verma, "Determination of optimum mixture design method for self-compacting concrete: Validation of method with experimental results," *Construction and Building Materials*, vol. 217, pp. 664-678, 2019.

[3] H. Okamura, K. Maekawa, and K. Ozawa, *High Performance Concrete*. Gihodo Publishing, 1993.

[4] H. Okamura and M. Ouchi, "Self-compacting concrete," *Journal of Advanced Concrete Technology*, vol. 1, no. 1, pp. 5–15, April 2003.

[5] S. H. Kosmatka and M. L. Wilson, "Chemical admixtures for concrete," in *Design and Control of Concrete Mixtures*, 15th ed. Illinois, PCA, 2011, ch. 7, pp. 117–136.

[6] A. Mardani-Aghabaglou, M. Tuyan, G. Yilmaz, Ö. Arıöz, and K. Ramyar, "Effect of different types of superplasticizer on fresh, rheological and strength properties of self-consolidating concrete," *Construction and Building Materials*, vol. 47, pp. 1020–1025, 2013.

[7] M. Liu, J. Lei, Y. Bi, X. Du, Q. Zhao, and X. Zhang, "Preparation of polycarboxylate-based superplasticizer and its effects on zeta potential and rheological property of cement paste," *Journal of Wuhan University of Technology-Mater. Sci. Ed.*, vol. 30, no. 5, pp. 1008–1012, 2015.

[8] X. Lin, B. Liao, J. Zhang, J. Huang, and H. Pang, "Synthesis and characterization of high-performance cross-linked polycarboxylate superplasticizers," *Construction and Building Materials*, vol. 210, pp. 162–171, 2019.

[9] M. G. Altun, S. Özen, and A. Mardani-Aghabaglou, "Effect of side chain length change of polycarboxylate-ether based high range water reducing admixture on properties of self-compacting concrete," *Construction and Building Materials*, vol. 246, p. 118427, 2020.

[10] S. Özen, M. G. Altun, and A. Mardani-Aghabaglou, "Effect of the polycarboxylate based water reducing admixture structure on self-compacting concrete properties: Main chain length," *Construction and Building Materials*, vol. 255, p. 119360, 2020.

[11] P. Jongvivatsakul, A. Attachaiyawuth, and W. Pansuk, "A crack-shear slip model of high-strength steel fiber-reinforced concrete based on push-off test," *Construction and Building Materials*, vol. 126, pp. 924–935, 2016.

[12] K. Turk, M. Bassurucu, and R. E. Bitkin, "Workability, strength and flexural toughness properties of hybrid steel fiber reinforced SCC with high-volume fiber," *Construction and Building Materials*, vol. 266, p. 120944, 2021.

[13] S. Grünewald and J. C. Walraven, "Self-compacting concrete: Materials, properties, and applications," in *Properties of Fibre Reinforced SCC*, R. Siddique, Ed. Cambridge, Woodhead Publishing, 2020, ch. 12, pp. 309–370.

[14] A. S. El-Dieb and M. M. Reda Taha, "Flow characteristics and acceptance criteria of fiber-reinforced self-compacted concrete (FR-SCC)," *Construction and Building Materials*, vol. 27, no. 1, pp. 585–596, 2016.

[15] T. Ponikiewski and J. Katzer, "Properties of fresh SCC mix reinforced by different types of steel and polymer fibre," *Construction and Building Materials*, vol. 62, pp. 96–101, 2014.

[16] L. Zhou, Y. Zheng, Y. Yu, G. Song, L. Huo and Y. Guo, "Experimental study of mechanical and fresh properties of HVFA-SCC with and without PP fibers," *Construction and Building Materials*, vol. 267, p. 121010, 2021.

[17] S. Y. Ghanem, J. Bowling, and Z. Sun, "Mechanical properties of hybrid synthetic fiber reinforced self-consolidating concrete," *Composites Part C: Open Access*, vol. 5, p. 100154, 2021.

[18] K. F. Li, C. Q. Yang, W. Huang, Y. B. Zhao, Y. Wang, Y. Pan, and F. Xu, "Effects of hybrid fibers on workability, mechanical, and time-dependent properties of high strength fiber-reinforced self-consolidating concrete," *Construction and Building Materials*, vol. 277, p. 122325, 2021.

[19] M. Vaishnavi, A. Aswathi, S. Sri Saarani, A. Varghese, D. Sathyan, and K. M. Mini, "Strength and workability characteristics of coir and nylon fiber reinforced self-compacting mortar," *Materials Today: Proceedings*, vol. 46, pp. 4696–4701, 2021.

[20] F. Kassimi and K. H. Khayat, "Mechanical properties of fiber-reinforced concrete with adapted rheology," *Cement and Concrete Composites*, vol. 118, p. 103958, 2021.

[21] H. S. Attar, M. R. Esfahani, and A. Ramezani, "Experimental investigation of flexural and shear strengthening of RC beams using fiber-reinforced self-consolidating concrete jackets," *Structures*, vol. 27, pp. 46–53, 2020.

[22] C. Zhang, S. Han, and Y. Hua, "Flexural performance of reinforced self-consolidating concrete beams containing hybrid fibers," *Construction and Building Materials*, vol. 174, pp. 11–23, 2018.

[23] W. Wang, A. Shen, Z. Lyu, Z. He, and K. T. Q. Nguyen, "Fresh and rheological characteristics of fiber reinforced concrete-A review," *Construction and Building Materials*, vol. 296, 2021.

[24] W. Pansuk, T. N. Nguyen, Y. Sato, J. A. Den Uijl, and J. C. Walraven, "Shear capacity of high performance fiber reinforced concrete I-beams," *Construction and Building Materials*, vol. 157, pp. 182–193, 2017.

[25] W. Wongkeo, P. Thongsanitgarn, A. Ngamjarurojana, and A. Chaipanich, "Compressive strength and chloride resistance of self-compacting concrete containing high level fly ash and silica fume," *Materials & Design*, vol. 64, pp. 261–269, 2014.

[26] S. C. Gnanaraj, R. B. Chokkalingam, G. L. Thankam, and S. K. M. Pothinathan, "Durability properties of self-compacting concrete developed with fly ash and ultra fine natural steatite powder," *Journal of Materials Research and Technology*, vol. 13, pp. 431–439, 2021.

[27] P. R. de Matos, M. Foiato, A. Ngamjarurojana, and L. R. Prudêncio, "Ecological, fresh state and long-term mechanical properties of high-volume fly ash high-performance self-compacting concrete," *Construction and Building Materials*, vol. 203, pp. 282–293, 2019.

[28] S. Barbhuiya, "Effects of fly ash and dolomite powder on the properties of self-compacting concrete," *Construction and Building Materials*, vol. 25, no. 8, pp. 3301–3305, 2019.

[29] S. Yang, J. Zhang, X. An, B. Qi, D. Shen, and M. Lv, "Effects of fly ash and limestone powder on the paste rheological thresholds of self-compacting concrete," *Construction and Building Materials*, vol. 281, p. 122560, 2021.

[30] G. Sua-iam and N. Makul, "Incorporation of high-volume fly ash waste and high-volume recycled alumina waste in the production of self-consolidating concrete," *Journal of Cleaner Production*, vol. 159, pp. 194–206, 2017.

[31] R. Siddique, "Properties of self-compacting concrete containing class F fly ash," *Materials & Design*, vol. 32, no. 3, pp. 1501–1507, 2011.

[32] P. Promsawat, B. Chatveera, G. Sua-iam, and N. Makul, "Properties of self-compacting concrete prepared with ternary Portland cement-high volume fly ash-calcium carbonate blends," *Case Studies in Construction Materials*, vol. 13, p. e00426, 2022.

[33] A. Jain, R. Gupta, and S. Chaudhary, "Sustainable development of self-compacting concrete by using granite waste and fly ash," *Construction and Building Materials*, vol. 262, p. 120516, 2020.

[34] F. A. Mustapha, A. Sulaiman, R. N. Mohamed, and S. A. Umara, "The effect of fly ash and silica fume on self-compacting high-performance concrete," *Materials Today: Proceedings*, vol. 39, pp. 965–969, 2021.

[35] O. Almuwbber, R. Haldenwang, W. Mbasha, and I. Masalova, "The influence of variation in cement characteristics on workability and strength of SCC with fly ash and slag additions," *Construction and Building Materials*, vol. 160, pp. 258–267, 2018.

[36] T. Daungwilailuk, P. Pheinsusom, and W. Pansuk, "Uniaxial load testing of large-scale 3D-printed concrete wall and finite-element model analysis," *Construction and Building Materials*, vol. 275, p. 122039, 2021.

[37] P. Nuaklong, J, Chittanurak, P, Jongvivatsakul, W, Pansuk, A, Lenwari, and S, Likitlersuang, "Effect of hybrid polypropylene-steel fibres on strength characteristics of UHPFRC," *Advances in Concrete Construction*, vol. 10, no. 1, pp. 1-11, 2020.

[38] A. Attachaiyawuth, S. Rath, K. Tanaka, and M. Ouchi, "Improvement of self-compactability of air-enhanced self-compacting concrete with fine entrained air," *Journal of Advanced Concrete Technology*, vol. 14, no. 3, pp. 55–69, 2016.

[39] S. Rath, N. Puthipad, A. Attachaiyawuth, and M. Ouchi, "Critical size of entrained air to stability of air volume in mortar of self-compacting concrete at fresh stage," *Journal of Advanced Concrete Technology*, vol. 15, no. 1, pp. 29–37, 2017.

[40] S. Rath, M. Ouchi, N. Puthipad, and A. Attachaiyawuth, "Improving the stability of entrained air in self-compacting concrete by optimizing the mix viscosity and air entraining agent dosage," *Construction and Building Materials*, vol. 148, pp. 531–537, 2017.

[41] N. Puthipad, M. Ouchi, S. Rath, and A. Attachaiyawuth, "Enhancement in self-compactability and stability in volume of entrained air in self-compacting concrete with high volume fly ash," *Construction and Building Materials*, vol. 128, pp. 349–360, 2016.

[42] N. Puthipad, M. Ouchi, and A. Attachaiyawuth, "Effects of fly ash, mixing procedure and type of air-entraining agent on coalescence of entrained air bubbles in mortar of self-compacting concrete at fresh state," *Construction and Building Materials*, vol. 180, pp. 437–444, 2018.

[43] B. Łaźniewska-Piekarczyk, "Analysis of the influence of type, amount and way of introduction of anti-foaming admixture (AFA) on the properties of self-compacting concrete mix," in *Brittle Matrix Composites 9*, A. M. Brandt and J. Olek, Eds. Cambridge: Woodhead Publishing, 2009, pp. 265–274.

[44] B. Łaźniewska-Piekarczyk, "The influence of selected new generation admixtures on the workability, air-voids parameters and frost-resistance of self compacting concrete," *Construction and Building Materials*, vol. 31, pp. 310–319, 2012.

[45] B. Łaźniewska-Piekarczyk and J. Szwabowski, "Stability of Air-content in the Case of Innovative Air-entraining Portland Multicomponent Cement," *Procedia Engineering*, vol. 108, pp. 559–567, 2015.

[46] N. Puthipad, M. Ouchi, S. Rath and A. Attachaiyawuth, "Enhanced entrainment of fine air bubbles in self-compacting concrete with high volume of fly ash using defoaming agent for improved entrained air stability and higher aggregate content," *Construction and Building Materials*, vol. 144, pp. 1–12, 2017.

[47] M. Ouchi, K. Kameshima, and A. Attachaiyawuth, "Improvement in self-compacting properties of fresh concrete by eliminating large air bubbles using an antifoaming agent," *Journal of Advanced Concrete Technology*, vol. 15, no. 1, pp. 10–18, 2017.

[48] *Standard Test Method for Microscopical Determination of Parameters of the Air-Void System in Hardened Concrete*, ASTM C-457, 2009.

[49] G. Fagerlund, "Air-pore instability and its effect on the concrete properties," *Nordic Concrete Research*, vol. 9, pp. 39–52, 1990.

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