- Technical Paper –

FINENESS OF AIR BUBBLES AFFECTED BY MIXING PROCEDURE IN MORTAR IN SELF-COMPACTING CONCRETE

Sovannsathya RATH*1, Anuwat ATTACHAIYAWUTH*2, Masahiro OUCHI*3

ABSTRACT

The purpose of this study is to introduce an approach in improving fineness of air bubbles to ensure stability of air and enhance self-compactability of air-enhanced self-compacting concrete (air-SCC). Experiments were conducted to clarify the effect of different mixing procedure, mixing time with air-entraining agent (AE), mixing time with superplasticizer (SP), and dosage of SP on the fineness of air bubbles. With an effective mixing procedure, increasing dosage of AE and adjusting mixing time with AE or mixing time with SP produced finer and more stable air bubbles.

Keywords: fineness of air bubbles, mixing procedure, fresh mortar, self-compacting concrete

1. INTRODUCTION

1.1 Air-enhanced self-compacting concrete

Conventional high strength self-compacting concrete (SCC) has been used particularly in congested reinforcing concrete and in complicated formwork where usage of vibrator was difficult or impossible. Air-enhanced self-compacting concrete (air-SCC) was developed to reduce unit cost of SCC by decreasing cement content. Air-SCC is a normal strength concrete with sufficient self-compactability level specified by JSCE (R_1) [1]. By increasing the water to cement ratio (W/C) and increasing the fine aggregate to mortar ratio (s/m), target air content of about 10% in air-SCC was required to be stable with fine air bubbles to mitigate the self-compactability. In this study, W/C was 45% by weight and s/m was 55% by volume. Mix-proportion of SCC and air-SCC are shown in Table 1.

Table 1 Examples of mix-proportion of SCC and air-SCC

	W/C (% by weight)	W*	C	S	G
		(kg/1m³ of concrete volume)			
SCC	30	188	627	763	772
air-SCC	45	134	298	1076	724

*water including SP and AE; W: water, C: cement, S: fine aggregate, G: coarse aggregate

1.2 Objective of research

Objective of this study is to identify the effects of mixing procedure and mix-proportion on fineness of air bubbles. Understanding the effect of each parameters including mixing methods, mixing time with AE, mixing time with SP, and dosage of AE or SP, is beneficial for adjustment process to achieve any target air content with satisfied stability of air and finer system of air bubbles.

1.3 Linear traverse method

To evaluate fineness of air bubbles, air distribution test of hardened mortar samples were conducted following standard test method for microscopical determination of parameters of the air-void system in hardened concrete (ASTM C 457), procedure A [2]. Each mortar sample was casted in cylinder mold of diameter 100mm and height 200mm. Three pieces were extracted from each hardened mortar sample at three positions (top, middle, and bottom). Thickness of each piece was 50mm. Both base sides of each piece were polished by grinding and gently cleaned before the microscopical air-void distribution test. Area for investigation was 60×60 mm^2 and total traversed length was 2615.9 mm. Parameters obtained from the measurement included total air content, specific surface of air and spacing factor. Total air content is a proportion of the air bubbles volume in the total volume of mortar and expressed as percentage by volume. Specific surface of air is defined as the surface area of the air bubbles divided by their volume and expressed in mm^2/mm^3. Specific surface area is an index indicating fineness of air bubbles. Higher value of specific surface area of air means finer air bubbles were obtained. Spacing factor is a parameter related to the maximum distance in the cement paste from the periphery of an air bubble and expressed in mm.

2. FINENESS OF AIR BUBBLES AFFECTED BY DIFFERENT MIXING PROCEDURE

2.1 Mixing procedure and mix-proportion

Modification on mixing procedure was found beneficial to produce satisfied air stability [3]. In this study, experiments were conducted with mortar of air-SCC. Mixer with rotation speed of 140±5 rpm was

*1 Ph. D. candidate, Graduate School of Engineering, Kochi University of Technology, JCI Student Member
*2 Post-doctoral researcher, Kochi University of Technology, JCI Member
*3 Prof., Dept. of Infrastructure System Engineering, Kochi University of Technology, JCI Member

used. Different mixing procedures of mortar are shown in Fig. 1. Method A is a simple mixing method in which after fine aggregate and cement were mixed for 30 seconds; water, SP, and AE were added and mixed for another 120 seconds.

Method B is called water-dividing mixing method in which water was divided into two portions. The first portion of water was fixed at 20% of cement weight. First of all, fine aggregate and cement were mixed for 30 seconds. Then, the first portion of mixing water and SP were added and mixed for 60 seconds. Finally, the rest portion of mixing water and AE were added and mixed for the last 60 seconds.

Method C is a mixing method in which SP and AE were separated from each other but without dividing water. First of all, fine aggregate and cement were mixed for 30 seconds. Then, water and SP were added and mixed for 60 seconds. Finally, AE was added and mixed for the last 60 seconds.

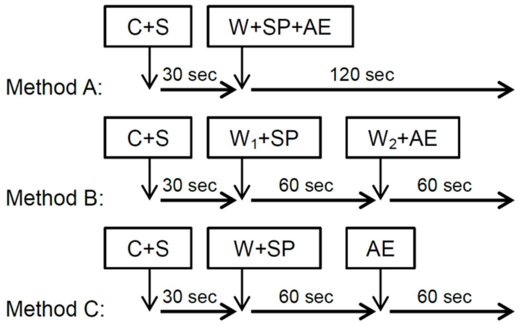

Fig. 1 Different mixing procedure of mortar; $W = W_1 + W_2$, W_1 = 20 % of cement weight

Materials used for mortar experiments in this study are shown in Table 2. Ordinary portland cement and crushed limestone sand were used. In this section, polycarboxylic based SP with viscosity agent, and AE of vinsol resin were used. Tests were conducted with two groups of three mortar samples produced by mixing method A, B and C with the same mix-proportion at AE dosage of 0.04% and 0.20% by cement weight. In all cases, W/C was 45% by weight, s/m was 55% by volume, and SP dosage was 1.4% of cement weight.

Table 2 Materials used for mortar experiments

Cement (C)	Ordinary Portland cement ($3.15g/cm^3$)
Fine aggregate (S)	Crushed limestone sand ($2.68g/cm^3$, F. M. 2.96)
Superplasticizer (SP)	SP_1: Polycarboxylic based with viscosity agent
	SP_2: Polycarboxylic based
Air-entraining agent (AE)	AE_1: Alkyl ether-based anionic surfactants
	AE_2: Vinsol resin

2.2 Results

At fresh stage, mortar flow, funnel speed (R_m), initial air content (A_{ini}), and air content at 2 hours (A_{2h}) were measured. The funnel speed was calculated from the V-funnel flow-through time (t_o) as shown in Eq. 1. Air content at hardened stage (A_{har}) and specific surface area of air (α) were determined through linear traverse method. All these parameters are shown in Table 3.

$$R_m = 10/t_o \quad (1)$$

Table 3 Properties of mortars produced by different mixing procedure

Name of sample	Flow (mm)	R_m	$A_{ini.}$ (%)	A_{2h} (%)	$A_{har.}$ (%)	α (mm^2/mm^3)
AE0.04%-A	259	2.35	17.5	14.4	12.8	14.79
AE0.04%-B	270	3.27	7.0	8.1	7.1	17.35
AE0.04%-C	267	2.26	8.9	10.4	10.6	14.65
AE0.20%-A	180	1.56	29.4	24.6	22.0	15.69
AE0.20%-B	258	3.18	9.8	10.6	8.8	22.38
AE0.20%-C	264	2.46	11.3	13.1	12.0	18.02

(1) Stability of air affected by mixing procedure

Relationship between initial air content and the variation in air content in 2 hours produced by method A, B and C at AE dosage of 0.04% and 0.20% of cement weight is shown in Fig. 2. At any dosage of AE, initial air content produced by method A was largely higher than that produced by method B or C. On the other hand, the stability of air was adequate with method B or C whereas the dramatic decrease in air content in 2 hours was occurred with method A.

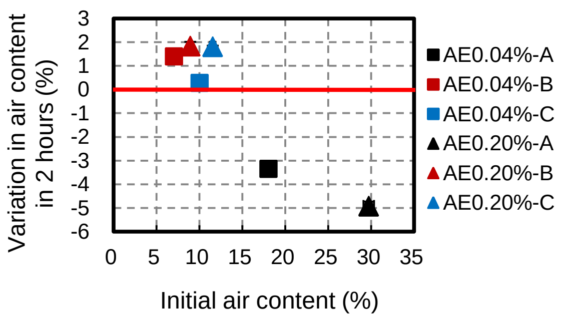

Fig. 2 Effect of different mixing procedure on initial air content and stability of air in fresh mortar

When SP was added and mixed before AE (in the case of method B or C), the electro-steric action of SP enables the dispersion of cement particles and releasing more pockets water into the mixture resulting in higher flowability as seen in Table 3. After adding AE, the well dispersed cement particles surrounded by negative charge of the polar chain and the steric hindrance would prevent the adhesion of air bubbles on the surface of cement particles providing less space for other air bubbles to be created. Furthermore, the well dispersed mixture could enhance the stability of air by reducing the rupturing of air bubbles due to friction between particles. Therefore, method B and C produced lower initial air content with better stability of air then method A. A slight increase in air content in 2 hours with method B or C was due to the coalescence between air bubbles forming a larger one with bigger volume than the sum of the original ones. The re-mixing of mortar for few seconds before test could also cause extra air bubbles.

(2) Improvement of fineness of air bubbles by mixing procedure and dosage of AE

Relationship between funnel speed and specific surface of air of mortar produced by different mixing procedure is shown in Fig. 3. Within the same dosage of AE, the mortar mixture of higher flowability (indicated by R_m) possessed higher value of specific surface of air. This result showed that method B and C produced finer system of air distribution than method A especially at higher dosage of AE. This result could be explained in accordance to the dispersing of the mixture. When the mixture was more dispersed, the repulsive force between particles was increased thus lowering the formation of coarse size air voids (which had lower pressure than the smaller ones). Therefore, the content of coarse size air bubbles in method B or C would be lower than that in method A.

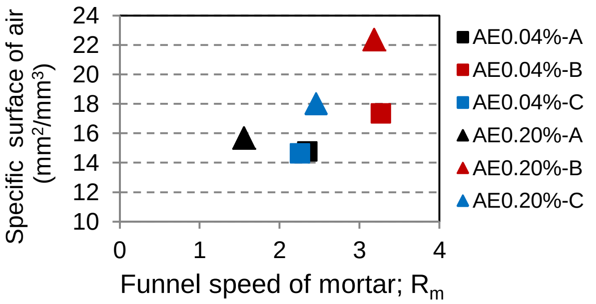

Fig. 3 Specific surface area of air of mortars produced by different mixing procedure

Air distribution of mortars produced by method A, B or C at AE dosage 0.20% of cement weight is shown in Fig. 4. Method B produced the finest system of air bubbles among these three mixing methods.With the same mix-proportion, method A produced largely higher initial air content than that of method B or C. However, most of the excessive content of air produced by method A was the coarse size air bubbles. It was interestingly observed that the content of coarse size air bubbles was considerably decreased when method B or C was used.

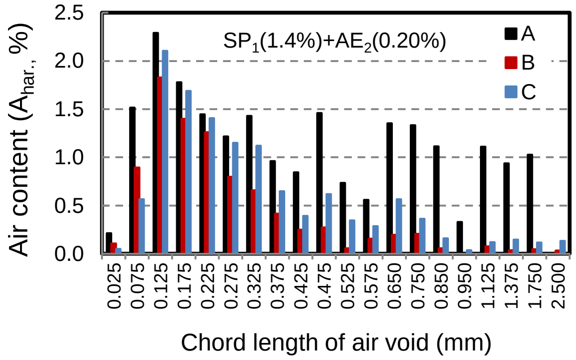

Fig. 4 Air distribution of mortars produced with AE dosage of 0.20% of cement weight

Share of air content at five chord length ranges of air bubbles of these six mortar samples is shown in Fig. 5. When dosage of AE increased from 0.04% to 0.20% of cement weight, in case of method A, share of air content at each chord length was not changed which means the fineness of air bubbles was not improved. On the other hand, with method B or C, share of air content of chord length smaller than 0.3mm increased while that of chord length larger than 0.5mm decreased which means the fineness of air bubbles was improved. Since method B or C could hinder the formation of coarse size air bubbles, increasing dosage of AE would increase mostly the fine size air bubbles and stabilize them from coalescence or rupturing. This result showed that with an effective mixing procedure, higher dosage of AE improved the fineness of air bubbles.

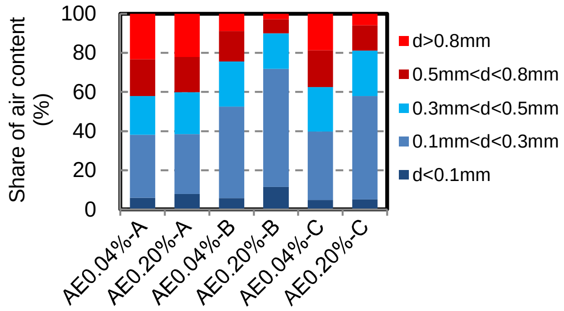

Fig. 5 Share of air content of mortars produced by method A, B or C

3. FINENESS OF AIR BUBBLES AFFECTED BY VARIATION IN MIXING TIME

3.1 Mixing procedure and mix-proportion

In this section, method C was modified as $C_{1,y}$ and $C_{x,2}$ to clarify respectively the effect of mixing time with AE ("y") and mixing time with SP ("x") on fineness of air bubbles. The mixing procedures of these mixing methods are shown in Fig. 6. The mixing time with AE, "y", was varied at 1 minute, 2 minutes and 3 minutes. The mixing time with SP, "x", was varied at 0, 0.5 minute, 1 minute, and 2 minutes.

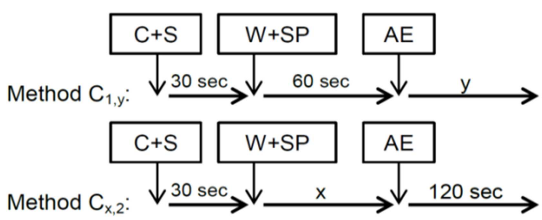

Fig. 6 Mixing procedure of method $C_{1,y}$ and $C_{x,2}$

In each case, the mix-proportion was kept the same by varying only the mixing time. W/C was 45% by weight and s/m was 55% by volume. In case of clarifying the effect of "y", SP of polycarboxylic based with viscosity agent and AE of vinsol resin were used. The dosage of SP and AE was 1.4% and 0.08% of cement weight respectively. In case of clarifying the effect of "x", SP of polycarboxylic based and AE of vinsol resin were used. The dosage of SP and AE was 0.8% and 0.08% of cement weight respectively.

3.2 Case 1: effect of mixing time with AE

The properties of three mortar samples tested in this case are shown in Table 4.

Table 4 Properties of mortars produced by different mixing time with AE

Name of sample	Flow (mm)	R_m	$A_{ini.}$ (%)	A_{2h} (%)	$A_{har.}$ (%)	α (mm^2/mm^3)
$C_{1,1}$-AE0.08%	235	2.35	13.1	14.0	14.3	15.03
$C_{1,2}$-AE0.08%	238	2.39	17.2	17.4	17.4	17.17
$C_{1,3}$-AE0.08%	249	2.27	21.0	20.4	17.3	16.53

(1) Stability of air affected by mixing time with AE

The relationship between initial air content and the variation in air content in 2 hours is shown in Fig. 7. Longer mixing time with AE resulted in higher initial air content and lower stability of air in 2 hours. Longer mixing time with AE means longer time of shearing action of the mixture thus providing more chance for air bubbles to be created. With the same dosage of AE, higher content of air was less stabilized than the lower content of air.

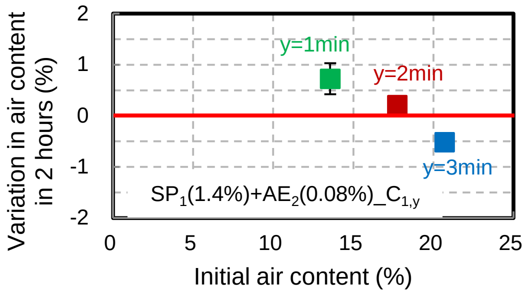

Fig. 7 Effect of mixing time with AE on initial air content and stability of air in fresh mortar

(2) Effect of mixing time with AE on fineness of air bubbles

The relationship between mixing time with AE and specific surface of air is shown in Fig. 8. When mixing time with AE was increased from 1 minute to 2 minutes, the specific surface of air was considerably increased. However, prolonging the mixing time with AE to 3 minutes slightly lowered the value of specific surface of air. This result showed that an optimum mixing time with AE existed, the time in which the finest system of air distribution could be obtained. When the shearing action of the mixture was increased due to longer mixing time of AE, more fine size air bubbles were formed. With enough dosage of AE, those fine size air bubbles would be well stabilized delaying the rate of coalescence and rupturing of air bubbles. When the mixing time with AE continued to be increased, the rate of coalescence between air bubbles increased thus lowering the content of fine size air bubbles and increasing the content of coarse size air bubbles. As a result, the stability of air was also decreased due to the rupturing or escaping of the coarser size air bubbles.

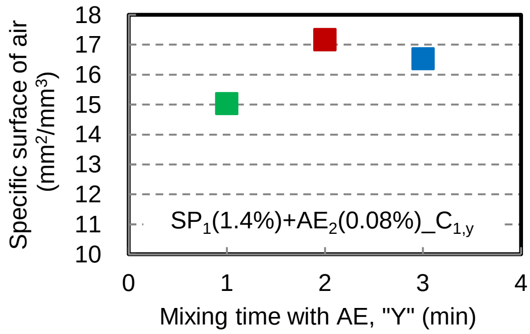

Fig. 8 Effect of mixing time with AE on specific surface of air

Air distribution of mortars produced by different mixing time with AE is shown in Fig. 9. When the mixing time with AE was increased from 1 minute to 2 minutes, the air content of chord length smaller than 0.45mm was increased while that of the larger chord length was slightly varied. When the mixing time with AE was increased to 3 minutes, the content of fine size air bubbles was slightly decreased while the content of coarse size air bubbles especially with the chord length larger than 0.60mm was increased. This result was due to the coalescence between air bubbles forming the larger size of air. The larger size air bubbles were less stable than the finer ones thus resulting in reduction in air content as shown in Fig. 7. Therefore, within this study scope, the improvement on fineness of air bubbles was able to achieve with increasing in the mixing time with AE up to 2 minutes.

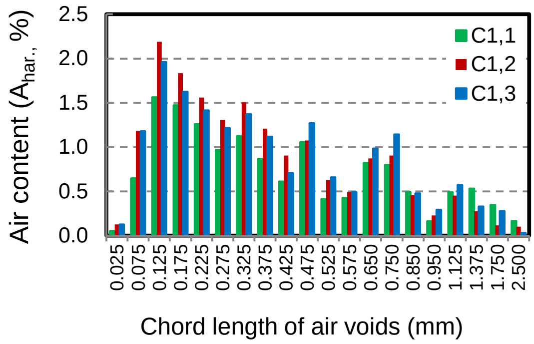

Fig. 9 Effect of mixing time with AE on air distribution of mortar

3.3 Case 2: effect of mixing time with SP

The properties of four mortar samples tested in this case are shown in Table 5.

Table 5 Properties of mortars produced by different mixing time with SP

Name of sample	Flow (mm)	R_m	$A_{ini.}$ (%)	A_{2h} (%)	$A_{har.}$ (%)	α (mm^2/mm^3)
$C_{0,2}$-AE0.08%	156	1.32	27.9	21.4	18.8	14.97
$C_{0.5,2}$-AE0.08%	233	2.02	19.0	18.3	15.3	16.15
$C_{1,2}$-AE0.08%	255	2.50	16.2	16.0	14.3	16.48
$C_{2,2}$-AE0.08%	261	2.62	17.3	17.3	16.2	16.49

(1) Stability of air affected by mixing time with SP

The relationship between initial air content and the variation in air content in 2 hours of mortars produced by different mixing time with SP is shown in Fig. 10. Longer mixing time with SP resulted in lower initial air content but improved the stability of air in 2 hours. With increasing mixing time with SP, the funnel speed of mortar (R_m) was accordingly increased which means the flowability of mortar was increased. The increase in flowability was due to the increase in dispersing action of mixture by prolonging the mixing time with SP before AE was added. The dispersed mixture due to SP action could hinder the formation of coarser size air bubbles having lower pressure thus resulting in lower air content. When the presence of coarse size air bubbles was lowered, the stability of air would be improved. As can be seen from Fig. 10, when the mixing time with SP was changed from 0 to 0.5 minute, a significant improvement on the stability of air was obtained while the initial air content was largely decreased. When the mixing time with SP was increased to 1 minute and then 2 minutes, the initial air content was gradually decreased and the stability of air was slightly improved.

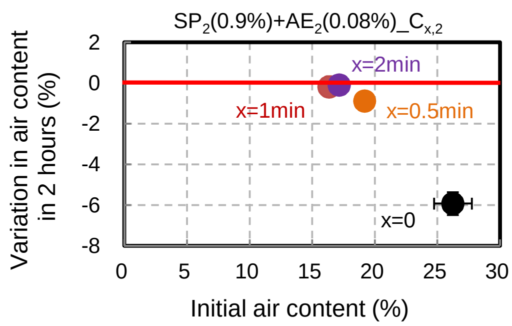

Fig. 10 Effect of mixing time with SP on initial air content and stability of air in fresh mortar

(2) Effect of mixing time with SP on fineness of air bubbles

The relationship between mixing time with SP and the specific surface of air is shown in Fig. 11. Longer mixing time with SP gradually increased the specific surface of air which means the fineness of air bubbles was improved. While longer mixing time with AE improved the fineness of air bubbles through forming more air content with fine size, longer mixing time with SP improved the fineness of air bubbles through hindering the formation of coarse size air bubbles. With the same dosage of AE, air distribution of the mixture with lower air content was more stable than that of the higher air content. The coalescence between air bubbles was also reduced with the mixture of lower air content (produced by longer mixing time with SP) thus maintaining the existence of the fine size air bubbles. Since the content of fine size air bubbles was maintained and the content of coarse size air bubbles was reduced, the fineness of air bubbles was improved with the longer mixing time with SP.

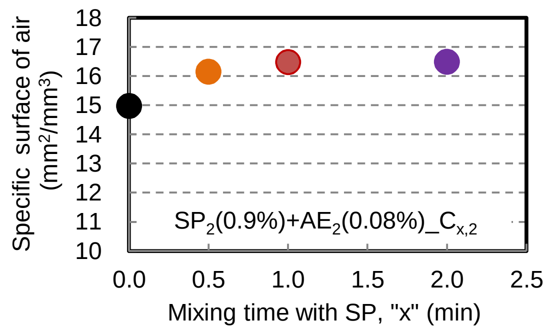

Fig. 11 Effect of mixing time with SP on specific surface of air

Air distribution of mortars produced by different mixing time with SP is shown in Fig. 12. When the mixing time with SP was increased, the content of coarse size air bubbles especially with chord length larger than 0.60mm was gradually decreased.

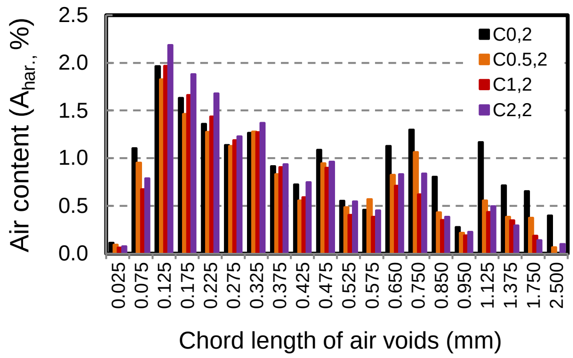

Fig. 12 Effect of mixing time with SP on air distribution of mortar

4. FINENESS OF AIR BUBBLES AFFECTED BY DOSAGE OF SUPERPLASTICIZER

4.1 Mixing procedure and mix-proportion

In this section, method C was modified as method $C_{2,2}$, as shown in Fig. 13, in which mixing time with SP was 120 seconds and mixing time with AE was also 120 seconds.

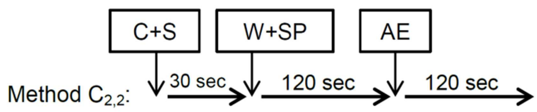

Fig. 13 Mixing procedure of method $C_{2,2}$

Three mortar samples were tests in this section to identify the effect of SP dosage on the fineness of air bubbles. The same mixing method with the same mixing time was conducted with these three mortar samples. For each sample, W/C was 45% by weight, s/m was 55% by volume, and the dosage of AE (alkyl ether-based) was 0.015% of cement weight. The dosage of SP (polycarboxylic based) was varied at 0.5%, 0.7 % and 0.8% of cement weight.

4.2 Results

The properties of three mortar samples tested in this case are shown in Table 6.

Table 6 Properties of mortar samples produced with different dosage of SP

Name of sample	Flow (mm)	R_m	$A_{ini.}$ (%)	A_{2h} (%)	$A_{har.}$ (%)	α (mm^2/mm^3)
$C_{2,2}$-SP0.5%	184	2.31	18.3	17.9	17.0	18.13
$C_{2,2}$-SP0.7%	244	2.82	17.9	18.1	17.3	20.74
$C_{2,2}$-SP0.8%	260	2.98	17.0	17.2	15.9	20.89

(1) Effect of dosage of SP on initial air content

The relationship between initial air content and the variation in air content in 2 hours is shown in Fig. 14. Higher dosage of SP resulted in lower initial air content while had no significant effect on the stability of air. Increasing the dosage of SP increased the flowability of the mortar (indicated by R_m) by the dispersing action of SP. The effect of higher dosage of SP worked in a similar way as the effect of longer mixing time with SP that could hinder the formation of coarse size air bubbles thus decreasing the initial air content.

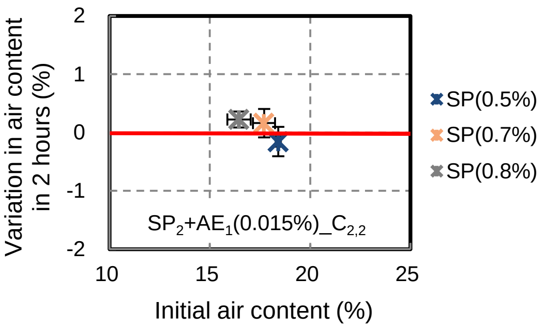

Fig. 14 Effect of dosage of SP on initial air content and air stability in 2 hours

(2) Effect of dosage of SP on fineness of air bubbles

The relationship between dosage of SP and the specific surface of air is shown in Fig. 15. The specific surface of air was gradually increased with the increase dosage of SP. The fineness of air bubbles was improved by increasing dosage of SP through the reduction in content of coarse size air bubbles.

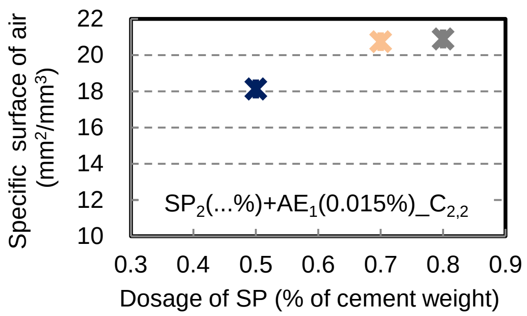

Fig. 15 Effect of dosage of SP on specific surface of air

Air distribution of mortars produced by different dosage of SP is shown in Fig. 16. When dosage of SP was increased, the content of coarse size air bubble especially with chord length larger than 0.70mm was significantly decreased while the content of fine size air bubbles was considerably increased. This graph clearly showed the improvement of fineness of air bubbles due to increasing in dosage of SP.

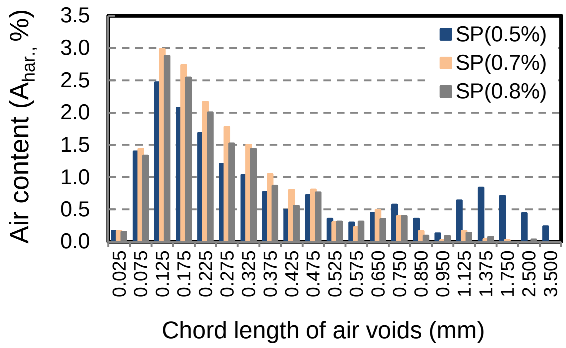

Fig. 16 Air distribution of mortars affected by dosage of SP

5. CONCLUSION

According to results and analysis in this study, conclusion can be written as following:

1) Mixing procedure in which SP was added and mixed before adding AE produced finer system of air bubbles than mixing procedure in which SP and AE were added and mixed at the same time. With the effective mixing procedure, increasing dosage of AE could also improve the fineness of air bubbles.
2) Longer mixing time with AE increased the content of fine size air bubbles thus improving the fineness of air bubbles. Longer mixing time with SP lowered the content of coarse size air bubbles thus improving the fineness of air bubbles.
3) Higher dosage of SP lowered the coarse size air content and increased the fine size air content thus improving the fineness of air bubbles.

REFERENCES

[1] "Recommendation for self-compacting concrete," JSCE Concrete Engineering Series 31, Aug. 1999

[2] "Standard test method for microscopical determination of parameters of the air-void system in hardened concrete," ASTM C457, 2009

[3] Sovannsathya, R., Anuwat, A. and Ouchi, M.," An effective and efficient mixing method for controlling initial air content with stability of entrained air in fresh mortar of self-compacting concrete," Proceedings of JCI, Vol. 37(1), 2015, pp. 1447-1452