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ORIGINAL ARTICLE

Development of Air-enhanced Self-compacting Concrete

Kenta Kameshima*, Anuwat ATTACHAIYAWUTH* and Masahiro OUCHI*
Kochi University of Technology*

***Abstract*:** This paper presents the self-compactability enhancement of mortar and concrete by entrained air. The sufficient level of self-compactability was achieved with air content of approximately 17% by simple mixing method. An effective mixing method called water dividing and AE dividing mixing method were introduced in order to increase level of self-compactability of fresh concrete. Self-compactability of concrete could be achieved with lower air content which was approximately 10% by water dividing mixing method. This resulted in the development of new type of self-compacting concrete (SCC) called air-enhanced self-compacting concrete (airSCC). This concrete was developed by making use of ball bearing effect of entrained air. Effective air bubble for airSCC was entrained with water-dividing mixing method and excessive dosage of air-entraining agent. These resulted in air-enhanced self-compactability of fresh concrete. Accordingly, aggregate amount in concrete mix proportions could be increased, resulted in the reduction in cement content in mix proportions.

Keywords: self-compacting concrete, water dividing mixing method, entrained air

1. INTRODUCTION

Self-compacting concrete (SCC) was developed over 25 years ago in order to improve durability of concrete structures. Cement or powder content of SCC is approximately 2 times higher than that of conventional concrete for achieving self-compactability of fresh concrete, as shown in Fig. 1. This resulted in high unit cost of SCC because unit cost of concrete mainly depends on cement content in mix proportion. Furthermore to avoid flowing obstruction by coarse aggregate, coarse aggregate content is limited approximately as 30% of unit volume of concrete. Presently, unit cost of SCC is approximately 2 times higher than unit cost of normal concrete, thus SCC has not been extensively used in many countries. In construction project, although the labor cost for concrete work could be reduced by employing SCC, total cost of concrete work is still high, comparing to that of concrete work using normal concrete.

The purpose of this study is to reduce unit cost of SCC by reducing unit cement content in mix proportion and maintain self-compactability of fresh concrete simultaneously. Entrained air is well known as the factor that is added to concrete mix in order to improve freezing and thawing resistance of concrete in the cold environment. Furthermore the secondary benefit of entrained air has been observed in workability enhancement. Slump of fresh concrete increased approximately 10 to 50 mm by increasing entrained air approximately 5%. Therefore entrained air might enhance flowability of SCC also. Flowability enhancement of SCC by entrained air is very interesting. Mortar and concrete experiment for examining effect of entrained air on flowability and self-compactability were conducted in this study.

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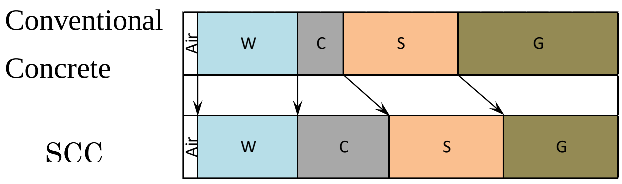

Fig.1 Mix proportion of Self-compacting concrete and conventional concrete

2. 2. TESTING PROCEDURE

To avoid laborious work of mixing concrete with real coarse aggregate, mortar experiment was firstly conducted by using model coarse aggregate in order to preliminary evaluate flowability of mortar itself. Subsequently mix proportions with high flowability will be applied to concrete experiment in order to evaluate properties of self-compacting concrete at fresh state. Flowability of mortar is represented as the degree of reduction in interaction between model coarse aggregate and mortar that will be described in next paragraph. The degree of interaction between model coarse aggregate and mortar was set up as an index for evaluating shear resistance of mortar and the normal stress occurred by the approaching of model coarse aggregate, which is represented self-compactability of fresh concrete during deformation. This mechanism is described in Fig. 2. The degree of interaction between model coarse aggregate and mortar is represented as ($1-R_{mb}/R_m$), which is obtained by the flowability of mortar (R_m) and mortar with model coarse aggregate (R_{mb}). R_m and R_{mb} are defined as equation (1) and (2) respectively, which are obtained from mortar funnel test, as shown in Fig. 3. Finally, the interaction between coarse aggregate and mortar ($1-R_{mb}/R_m$) could be used as the preliminary index for evaluating the appropriate mortar for self-compacting concrete.

$$R_m = \frac{10}{t_m} \quad (1)$$

$$R_{mb} = \frac{10}{t_{mb}} \quad (2)$$

where,

t_m : funnel time of mortar

t_{mb} : funnel time of mortar with model coarse aggregate

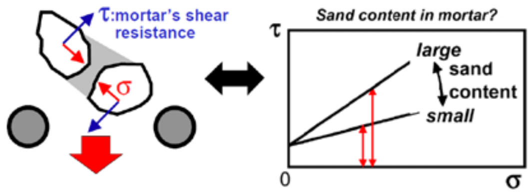

Fig.2 Shear resistance of mortar (τ) in accordance with normal stress (σ)

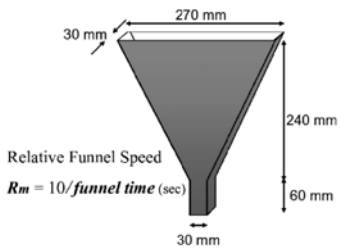

Fig. 3 Mortar funnel test

The degree of interaction between model coarse aggregate and mortar ($1-R_{mb}/R_m$) has been significantly related to the filling height of concrete box test, which is a representative of self-compactability of fresh concrete, as shown in Fig. 4. Therefore the index of ($1-R_{mb}/R_m$) is capable to be used to preliminary evaluate self-compactability of fresh concrete.

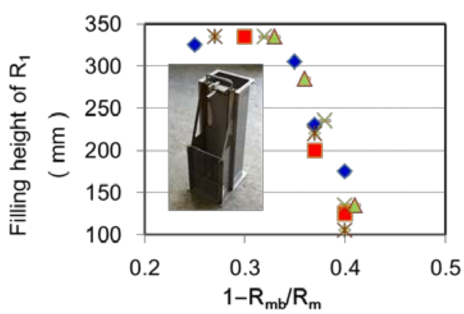

Fig. 4 Relationship between ($1-R_{mb}/R_m$) and filling height of concrete box test

3. AIR-ENHANCED SELF-COMPACTABILITY WITH SIMPLE MIXING METHOD

In this series, 2 types of superplasticizer (SP1: Conventional type of superplasticizer ,SP2: New type of superplasticizer) and 3 types of air entraining agent were used. Ordinary portland cement (OPC) was used as cementitious material. Water cement ratio (W/C) and Sand to mortar ratio were fixed as 45% by weight and 55% by volume respectively. Total coarse aggregate is 30% of volume of concrete. The target flow diameter is in range of 600-700 mm by adjusting dosage of superplasticizer.

Cement, sand and coarse aggregate were mixed for 30 seconds. Then liquid materials (water, superplasticizer, air entraining agent) were added and mixed for 2 minutes for mortar and 3 minutes for concrete. Slump-flow test, air contents test and box test (R1:Steal bars) were tested for fresh concrete was tested by. Materials used in this study are given in table1.

Table1 Materials used

<table>
<tr><td>Cement</td><td colspan="2">Ordinary portland cement (3.15g/cm³)</td></tr>
<tr><td>Fine aggregate</td><td colspan="2">Crushed limestone sand (2.68g/cm³ , F.M 2.73)</td></tr>
<tr><td>Coarse aggregate</td><td colspan="2">Limestone (2.7g/cm³, F.M.6.7)
Size 5-15 mm 60%
Size 15-20 mm 40%
Total coarse aggregate is 30 % of volume of concrete</td></tr>
<tr><td>Conventional type of SP (SP1)</td><td colspan="2">Superplasticizer without viscosity agent 8SB</td></tr>
<tr><td>New type of SP (SP2)</td><td colspan="2">Superplasticizer blended with viscosity agent (6550)</td></tr>
<tr><td rowspan="3">Air entraining agent</td><td>AE1</td><td>101</td></tr>
<tr><td>AE2</td><td>Vinsol</td></tr>
<tr><td>AE3</td><td>101+ 785</td></tr>
</table>

3.1 Level of self-compactability of fresh concrete

Relationship between air content and filling height of concrete box test with SP1 is shown in Fig. 5. Filling height of fresh concrete gradually increased due to the increase in air content. Sufficient self-compactability (300mm) was achieved with air content of over 17% by using every type of air entraining agent. It can be seen that no significant difference of level of self-compactability due to different type of AE, the different filling height was mainly due to amount of air content.

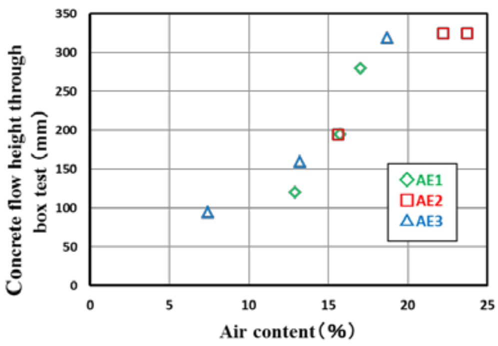

Fig. 5 Relationship between air content and concrete flow height box test with SP1

Moreover, Relationship between air content and concrete flow height box test with SP2 is shown in Fig. 6. Filling height of 300mm was achieved with air content of over 17% by using any type of AE with SP2. On the other hand, it was found that air content of approximately 10-15% was sufficient to achieve filling height of 300mm by using AE2 and combination of AE2 and AE3 with SP2.

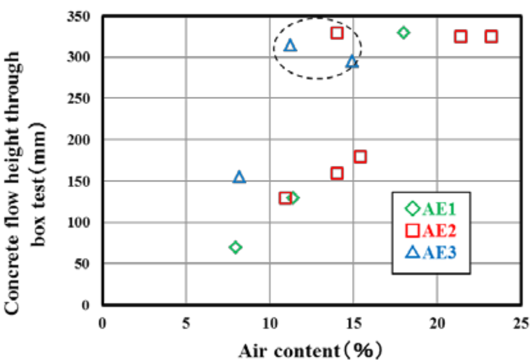

Fig. 6 Relationship between air content and concrete flow height box test with SP2

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3.2 Effect of air content on compressive strength

Fig. 7 shows the reduction in compressive strength due to the increase in air content in concrete specimens. It can be seen that compressive strength gradually reduced due to the increase in air content. Compressive strength of concrete with entrained air was compared with that of normal concrete. To achieve compressive strength similar to that of normal concrete, air content has to be lower than 10%, otherwise compressive strength will be low which is the main problem of concrete properties.

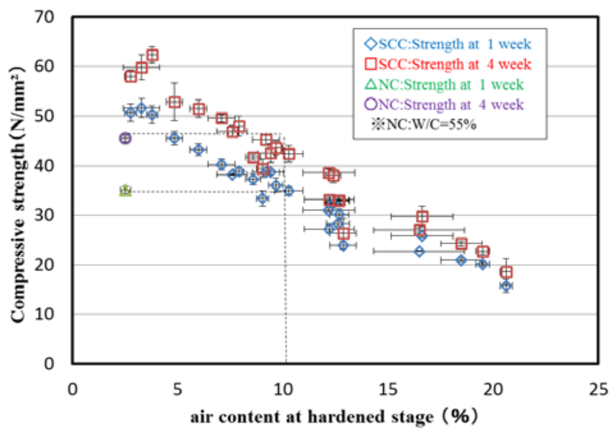

Fig. 7 Relationship between air content at hardened stage and Compressive strength

3.3. Reduction in air content

The amount of reduction in air content was in range of 2-6%. It tended to reduce due to the increase in air content as shown in Fig. 8.

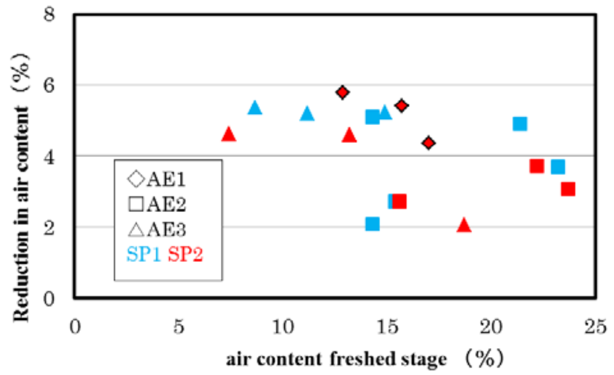

Fig. 8 Reduction in air content

4. SELF-COMPACTABILITY ENHANCEMENT BY ENTRAINED AIR WITH WATER DIVIDING MIXING METHOD

4.1 Mixing process

Simple mixing method is shown in Fig. 9. And water dividing mixing method was introduced in order to improve both durability and flowability of mortar. Water dividing mixing method is shown in Fig. 10. Firstly, cement and sand were mixed together for 30 seconds, and then 50% of water with superplasticizer were added and mixed for 60 seconds. At this step, authors tried to make mortar soft before adding air entraining agent. This might affect characteristic of air bubbles in mortar. Then another 50% of water with air entraining agent were added and mixed for 60 seconds. Moreover authors introduced AE dividing mixing method in order to make mortar portion before adding AE softer than water dividing method, AE dividing mixing method is shown in Fig. 11. Once the proper mortar was achieved, air content was measured, then flowability test of mortar (R_m) was measured, then glass beads was added to mortar and stirred for 20 times, finally flowability of mortar with model coarse aggregate (R_{mb}) were measured. The proper mortar mix was repeated 2 more times to confirm the stability of the results.

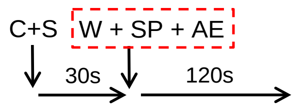

Fig. 9 Simple mixing method

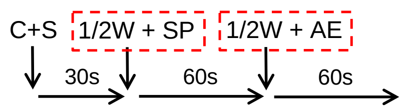

Fig. 10 Water dividing mixing method

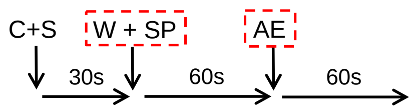

Fig. 11 AE dividing mixing method

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4.2 Mix proportions of mortar

Sand to mortar ratio by volume (s/m) was designed first in order to fix amount of solid particles in mix. Designed s/m was 57% with target air content was approximately in range of 10 to 13%, thus s/m including air content became approximately in range of 50 to 52%. Mix proportion without entrained air with designed s/m of 51% was conducted using either type of superplasticizer as control mix in order to study effect of the presence of entrained air on flowability of mortar. W/C of every mix proportion was fixed as 45%. To achieve target air content, dosage of air entraining agent was varied depending on the type of superplasticizer and type of air entraining agent. Mix proportions of mortar are listed in Table 2.

Table 2. Mix proportions of mortar

Mixing method	W/C	s/m	SP	AE	AE dosage (% of cement)
Simple method	45%	51%	SP1	-	-
		57%		AE1	0.011
				AE2	0.008
Water div. method		51%	SP2	-	-
		57%		AE1	0.211
				AE2	0.158
AE div.		57%		AE1	0.158

4.3 Mitigation of interaction between coarse aggregate and mortar ($1-R_{mb}/R_m$) by effective mixing method with entrained air

Fig. 12 shows mitigation of ($1-R_{mb}/R_m$) regarding to s/m including air content. The s/m including air content was approximately 50% in all mixes. ($1-R_{mb}/R_m$)depended on the amount of solid particles in mortar matrix, Ball-bearing effect by entrained air existed and it was apparently observed in case of mix using combination of SP2 and AE1 with water dividing or AE dividing mixing method. By using water dividing or AE dividing mixing method with SP2, dosage of air entraining agent was much higher than that of mixes using SP1, as shown in Table 2. In order to achieve air content approximately of 10 to 13%, the dosage of air entraining agent was approximately 20 times higher than mixes using SP1. Excessive dosage of AE with water dividing and AE dividing mixing method might produce preferable air bubbles for flowability enhancement. Although viscosity agent in new type of SP resulted in negative result on flowability, flowability was effectively enhanced by water dividing or AE dividing mixing method with high dosage of air entraining agent.

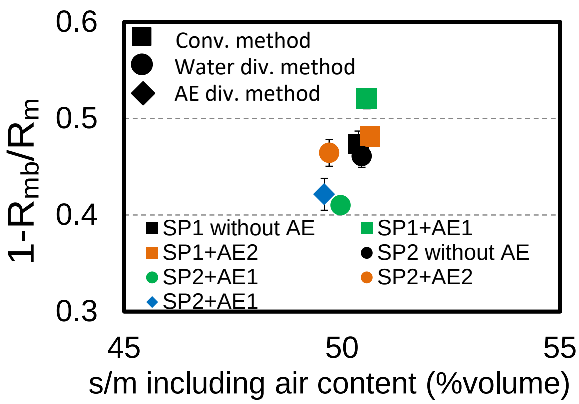

Fig. 12 Mitigation in $1-R_{mb}/R_m$ regarding to s/m including air content

4.4 Verification with concrete test

To ensure applicability of the results of mortar experiment into concrete for practical use, some of the mix proportions of mortar were applied to concrete experiment. Mortar mix proportions with new type of superplasticizer (SP2) were selected for concrete experiment. And mix proportion with the simple mixing method was also conducted in order to compare the efficiency of mixing method on self-compactability of fresh concrete. Mix-proportions of concrete experiment are listed in Table 3.

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Table 3. Mix proportions of concrete experiment

Mixing method	W/C	s/m	c/a	SP	AE	AE dosage(% of cement)
Simple method	45%	55%	30%	SP2	AE1	0.150
						0.005
Water dividing method						0.005
						0.050
						0.100
						0.150
						0.200
AE dividing method						0.150

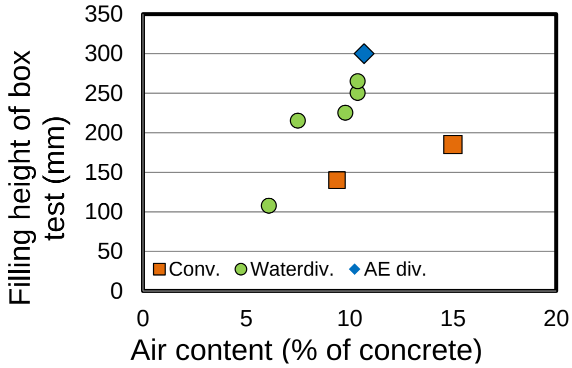

Fig. 13 Filling of fresh concrete

Self-compactability of fresh concrete was tested by box test which has been using extensively. Fig. 13 shows relationship between the air content and the filling height of concrete which represents self-compactability of fresh concrete. The air content was varied due to the difference in mixing method or dosage of AE. In cases of mix proportions with simple mixing method, filling height of mixes with AE of 0.005% and 0.15% were 140 mm and 180 mm respectively. Although the air content was approximately 10%, the filling height was only 140 mm. Once AE was increased to be 0.15%, air content was also increased to 15%. Nevertheless filling height was still less than 200 mm. In cases of mix-proportions with the water dividing mixing method, the filling height of concrete increased due to the increase in the dosage of AE, which reached 250 mm with the AE dosage of AE of over 0.15%. Although the air content of the mixes with AE of 0.1%, 0.15% and 0.2% were almost approximately as 10%, self-compactability was increased with the increase in the AE dosage. In this case, the maximum filling height of concrete was up to 265 mm with the dosage AE of 0.20% of the cement weight. Moreover, the filling height reached 300 mm by the AE dividing mixing method with AE of 0.15%.

Fig. 14 shows the tentative mix proportions and the filling height of conventional SCC and airSCC regarding to the mixing method. Conventional SCC with W/C of 30%, s/m of 45% and air content approximately of 4% has filling height of 300 mm. On the other hand, W/C and s/m of airSCC could be increased up to 45% and 55% respectively with the entrained air content of approximately 10%. The volume fraction of materials in each type of concrete is shown in Fig. 15.

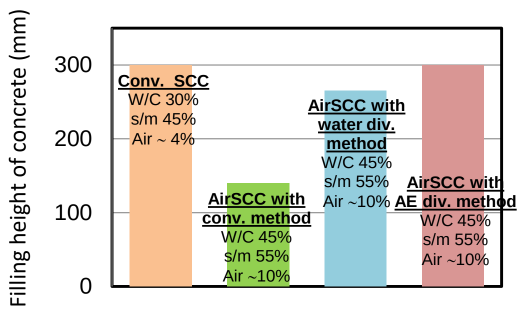

Fig. 14 Filling height of fresh concrete with different mixing method

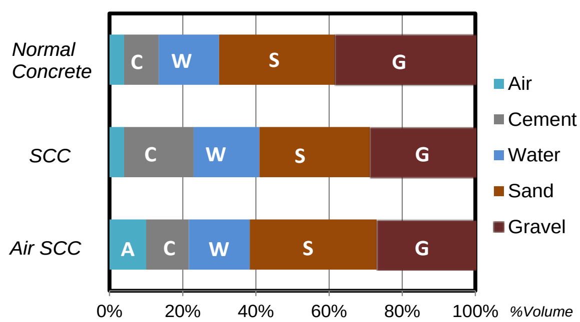

Fig. 15 Volume fraction of materials in concrete

Table 4. Mix proportions of concrete experiment

Type of concrete	Mass of materials (kg/m^3)					
	Cement	Water	Sand	Gravel	SP	AE
SCC (air ~ 4%)	599	180	810	778	6.6	-
airSCC (air ~ 10%)	369	166	929	729	4.1	0.6

Unit weight of materials used in 1 m^3 of concrete volume for conventional SCC with air content approximately of 4% and airSCC with air content approximately of 10% are shown in Table 4. Conventional SCC needs cement content approximately of 600 kg/m^3. Cement content in airSCC is approximately of 370 kg/m^3, which is lower than that of conventional SCC according to the increase in s/m in mix. Furthermore, when volume of concrete increase by air, weight of all materials, considering 1 m^3 is automatically decreased due to the replacement by volume of air, resulted in simultaneous reduction in all materials in mix.

5. CONCLUSIONS

The authors have succeeded in enhancing self-compactability of fresh concrete by employment of entrained air which is produced by an effective mixing method. Experimental results are summarized and written as follows:

(1) High level of self-compactability could be achieved with air content of over 17% by simple mixing method which was high. It significantly reduced compressive strength itself.

(2) Water dividing or AE dividing mixing method was effective in enhancing self-compactability of fresh concrete, especially for mixes with new type of superplasticizer and excessive dosage of air entraining agent. When the flowability of mortar just before adding AE during mixing was higher, it was appropriate for producing preferable characteristic of entrained air bubbles for enhancing self-compactability of fresh concrete.

(3) AirSCC, a new type of SCC with lower cement content and the entrained air content of approximately of 10% has been succeeded. This type of concrete could be alternative materials as low cost SCC for construction projects in which the budget is the first priority.

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