- Technical Paper -

AIR-ENHANCED SELF-COMPACTABILITY OF FRESH CONCRETE WITH EFFECTIVE MIXING METHOD

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ABSTRACT

Air-enhanced self-compacting concrete (airSCC) 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. Moreover the loss of entrained air during fresh stage was very small or air content slightly increased in some mixes. Accordingly, aggregate amount in concrete mix proportions could be increased, resulted in the reduction in cement content in mix proportions.

Keywords: self-compacting concrete, air-enhanced self-compactability, ball-bearing effect by entrained air, water-dividing mixing method, excessive dosage of air-entraining agent

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 interruption by coarse aggregate, coarse aggregate content is limited approximately as 30% of unit volume of concrete [2]. 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 labour 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 aim 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.

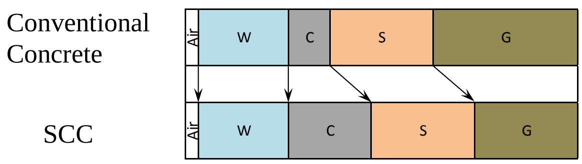

Fig. 1 Mix proportion of Self-compacting concrete and conventional concrete [1]

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% [3]. 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. Effect of entrained air on flowability of fresh mortar was plainly explained as "Ball-bearing Effect" as shown in Fig. 2 [4], that entrained air in concrete matrix behaves like ball bearing to fine aggregate particles by trundling. However effectiveness of ball bearing effect depended on combination type of superplasticizer and air entraining agent [4]. The loss of flowability of mortar which is represented as the increase of $1\text{-}R_{mb}/R_m$ due to the presence of entrained by conventional mixing method was observed in mixes with conventional type of SP (SP1) and new type of SP (SP2) as shown in Fig. 3. One of disadvantages of mixing method in previous research was durability of entrained air itself. Air content reduced approximately 40% after 1 hour. during fresh state, resulted in the reduction in flowability of mortar due to the insufficient air content, thus water dividing mixing method was performed in order to improve ball bearing effect and durability of entrained air simultaneously.

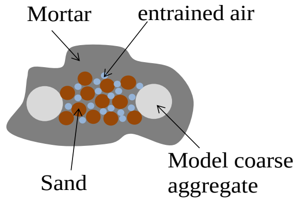

Fig. 2 Ball bearing effect by entrained air [4]

The effective mixing method with combination type of

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superplasticizer and air entraining agent for improving ball bearing effect in mortar and concrete were also presented.

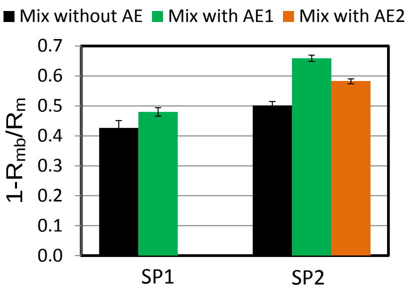

Fig. 3 Negative effect on flowability of mortar by entrained air with conventional mixing method

The purpose of this study is to improve flowability and durability of entrained air itself of SCC by entraining air in mix proportion with effective mixing method. Self-compacting concrete with flowability enhancement by entrained air was named as Air-enhanced SCC (airSCC), which contains air content approximately of 10% and maintains self-compactability equal to that of conventional SCC. Althought, durability of airSCC such as carbonation resistance has not been verified, the authors have verified that compressive strength and permeability of airSCC with air content approximately of 10% was similar to that of normal concrete with W/C of 55% and air content of 5%.

2. TESTING METHOD FOR EVALUATING DEGREE OF INTERACTION BETWEEN COARSE AGGREGATE AND MORTAR

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 indicating the correlation between 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. 4 [5]. The degree of interaction between model coarse aggregate and mortar is represented as 1-$\boldsymbol{R_{mb}}/\boldsymbol{R_m}$, which is obtained by the flowability of mortar ($\boldsymbol{R_m}$) and mortar with model coarse aggregate ($\boldsymbol{R_{mb}}$). $\boldsymbol{R_m}$ and $\boldsymbol{R_{mb}}$ are defined as equation (1) and (2) respectively, which are obtained from mortar funnel test [6], as shown in Fig. 5. Finally, the interaction between coarse aggregate and mortar (1-$\boldsymbol{R_{mb}}/\boldsymbol{R_m}$) could be used as the preliminary index for evaluating the appropriate mortar for self-compacting concrete.

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

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

where,

$\boldsymbol{t_m}$: funnel time of mortar

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

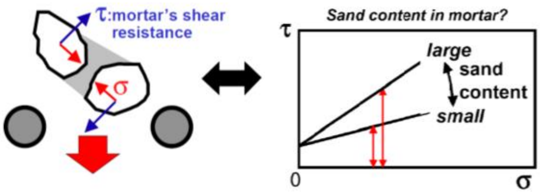

Fig.4 Shear resistance of mortar (τ) in accordance with normal stress (σ) [5]

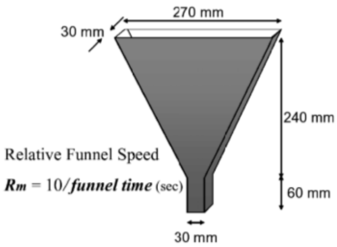

Fig. 5 Mortar funnel test [6]

The degree of interaction between model coarse aggregate and mortar (1-$\boldsymbol{R_{mb}}/\boldsymbol{R_m}$) 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. 6. Therefore the index of 1-$\boldsymbol{R_{mb}}/\boldsymbol{R_m}$ is capable to be used to preliminary evaluate self-compactability of fresh concrete.

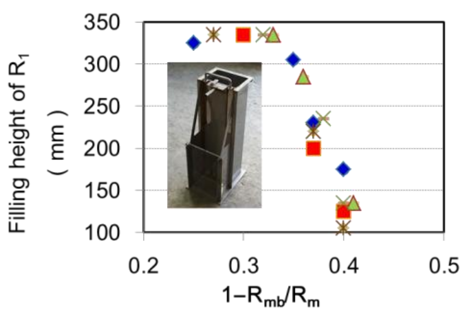

Fig. 6 Relationship between 1-R_{mb}/R_m and filling height of concrete box test

3. WATER DIVIDING MIXING METHOD WITH ENTRAINED AIR

3.1 Mixing process

Mortar test were conducted in a controlled room in which the temperature and relative humidity were constant at 20°c and 95% respectively. Every mix proportion was mixed by the same process, which is very punctual to the time in each step. Conventional mixing method is shown in Fig. 7. Firstly, cement and sand were mixed together for 30 seconds, and then liquid materials (water, superplasticizer and air-entraining agent) were added and mixed for 120 seconds. According to a previous research [4], flowability of mortar could not sufficiently be improved and durability of entrained air was also low by conventional mixing method, thus water dividing mixing method was introduced in order to improve both durability and flowability of mortar. Water dividing mixing method is shown in Fig. 8. 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. 9. Deformability of mortar was measured by mortar flow cone at 5 minutes, subsequently flowability test by funnel was performed. Deformability of mortar (***G_m***) was calculated in accordance with Fig. 10. Deformability test was performed again at 20 minutes. Mortar must be satisfied the proper mortar, which has Γ_m in range of 5.5 to 6.5 (cone flow is in range 255 to 275mm), otherwise mix proportion will be adjusted and mix from the first step until it satisfies the cone flow range. 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.

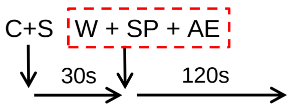

Fig. 7 Conventional mixing method

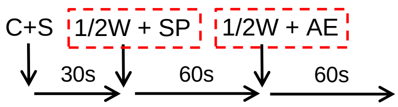

Fig. 8 Water dividing mixing method

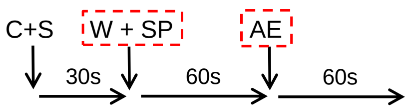

Fig. 9 AE dividing mixing method

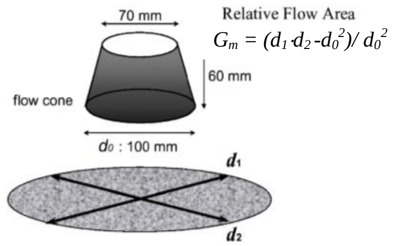

Fig. 10 Mortar flow test [6]

3.2 Materials used

Materials used in this study were available on the market in Japan. Ordinary portland cement (OPC) is used as a main cementitious materials for mortar and concrete. Fine aggregate was crushed lime stone sand which is extensively used for concrete in Japan. Coarse aggregate was limestone gravel. Glass beads with 10 mm diameter size was applied in mortar mix instead of real coarse aggregate because it has a uniform shape, thus effect of any factors on flowability of mortar can be clearly evaluated. 2 types of superplasticizer were used, which were conventional type and new type of superplasticizer respectively. Conventional one has been developed more than 15 years ago which is suitable for conventional SCC. Recently, new type of superplasticizer has been developed by blending with viscosity agent in order to increase viscosity of fresh concrete. By using new type one, water to cement ratio (W/C) can be increased up to 45% without segregation. 2 types of air entraining agent were used, which were different in chemical ingredients based. Materials used in this study are given in Table 1.

Table 1. Materials used

Cement	Ordinary portland cement (3.15 g/cm^3)
Fine aggregate	Crushed limestone sand (2.68 g/cm^3, F.M. 2.72)
Coarse aggregate	Limestone (2.7 g/cm^3, F.M. 6.76) Size 5-15 mm 60% Size 15-20 mm 40% Total coarse aggregate is 30% of volume of concrete
Model coarse aggregate	Glass beads (2.55 g/cm^3, uniform diameter of 10 mm.) 20% of volume of mortar
Conventional type of SP (SP1)	Superplasticizer without viscosity agent
New type of SP (SP2)	Superplasticizer blended with viscosity agent
Master Grenium 101 (AE1)	Alkyl ether-based
Vinsol (AE2)	Anionic surfactant

3.3 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)
Conv. 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%	SP2	AE1	0.158

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

The mitigation of interaction between coarse aggregate and mortar (1-R_{mb}/R_m) was succeeded by water dividing and AE dividing mixing method with combination of new type of superplasticizer (SP2) and AE1, as shown in Fig. 11. **On the other hand**, negative result on flowability of mortar occurred by using AE1 with conventional SP (SP1). And no significant results were found in mixes using AE2, in both mixes using SP1 and SP2. Flowability of mortar could be enhanced by entrained air by combination of SP2 and AE1 with water dividing mixing method. In cases of mix proportions with conventional mixing method, 1-R_{mb}/R_m increased in all the mixes due to the presence of entrained air. Moreover, 1-R_{mb}/R_m of mix proportion with AE2 and SP 1 could not be plotted because mortar with glass beads stopped during funnel test.

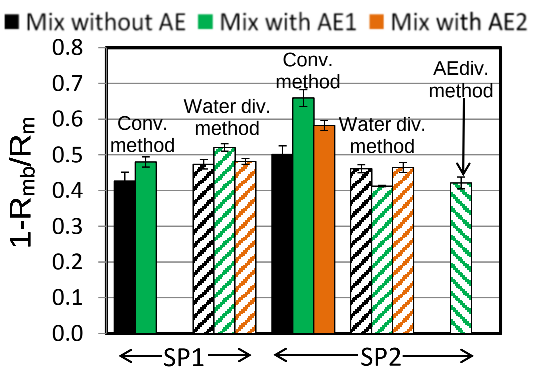

Fig. 11 Mitigation in 1-R_{mb}/R_m by water dividing mixing method with entrained air

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.

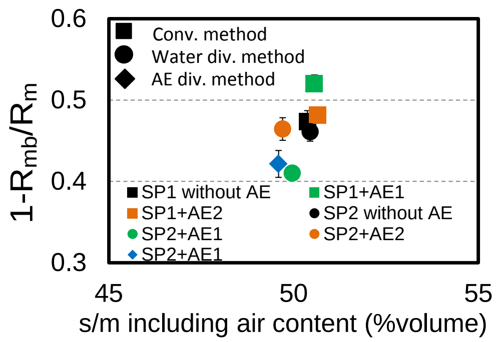

Fig. 12 Mitigation in 1-R_{mb}/R_m regarding to s/m including air content

4. 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 conventional 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.

Table 3. Mix proportions of concrete experiment

Mixing method	W/C	s/m	c/a	SP	AE	AE dosage(% of cement)
Convent-ional 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

Self-compactability of fresh concrete was tested by box test as shown in Fig. 13. Fig. 14 shows durability of entrained air in fresh concrete in 1 hour. Considering the mix-proportion with AE of 0.005%, it can be seen that air content decreased approximately from 9% to 5% in case of mix with the conventional mixing method and air content decreased approximately from 6% to 5% in case of mix with the water dividing mixing method.

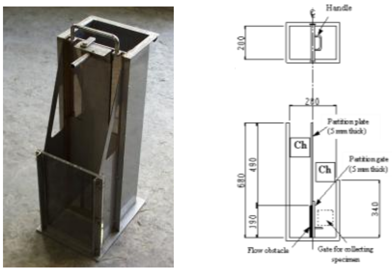

Fig. 13 Self-compactability test for concrete

Durability of air was poor by the conventional mixing method. Although durability of air was better due to the water dividing mixing method, air content was approximately 5% to 6% which was not sufficient for enhancing self-compactability of fresh concrete. Therefore dosage of AE was increased. Mix proportions with AE of 0.15% were selected to compare with mixes with AE of 0.005%. It can be seen apparently that air content increased approximately to be 10% to 12% in cases of mix with the water dividing or AE dividing mixing method, and approximately of 15% in case of mix with conventional mixing method. Air content was not decreased in 1 hour, it almost stable as 15% in case of mix with conventional mixing method, and air content increased approximately of 2% in cases of mix with water dividing and AE dividing mixing method. Therefore durability of air could be improved by increasing of AE dosage.

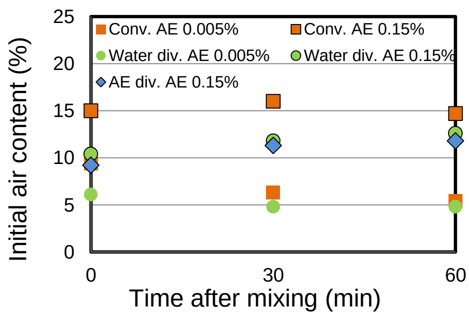

Fig. 14 Durability of air in 1 hour at fresh stage

Self-compactability of fresh concrete was tested by box test which has been using extensively. Fig. 15 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 difference in mixing method or dosage of AE. In cases of mix-proportions with the conventional 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, as shown in Fig. 16a). 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, as shown in Fig. 16b) 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% as shown in Fig. 16c).

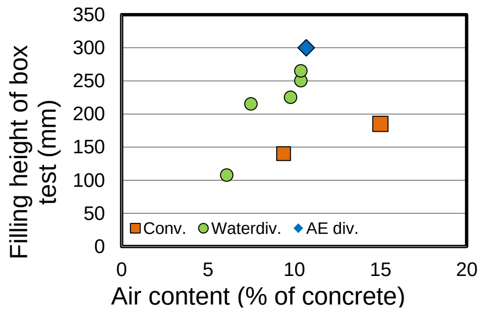

Fig. 15 Filling height of fresh concrete

a) b) c)

Fig. 16 Self-compactability test of fresh concrete
a) Conventional method (AE 0.005%)
b) Water dividing method (AE 0.15%)
c) AE dividing method (AE 0.15%)

It can be concluded that mortar with higher flowability just before adding AE during mixing and excessive dosage of AE resulted in enhanced self-compactability of SCC. Mortar before adding AE in the water dividing mixing method needed higher dosage of AE for achieving air content approximately of 10%, comparing to that in conventional mixing method. These might produce preferable characteristics of air bubbles for improving self-compactability of fresh concrete.

A relationship between $1\text{-}\boldsymbol{R_{mb}}/\boldsymbol{R_m}$ of mortar and filling of concrete with air content approximately of 10% could be clearly observed as shown in Fig. 17.

These 5 mixes contained almost the same exact amount of aggregate (s/m and G) in concrete according to the same design amount of aggregate and air content (approximately 10%). The filling height of concrete increased in accordance with the decrease in $1\text{-}\boldsymbol{R_{mb}}/\boldsymbol{R_m}$.

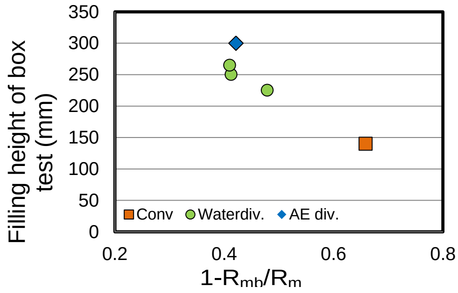

Fig. 17 1-R_{mb}/R_m and filling height of concrete

Fig. 18 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. 19.

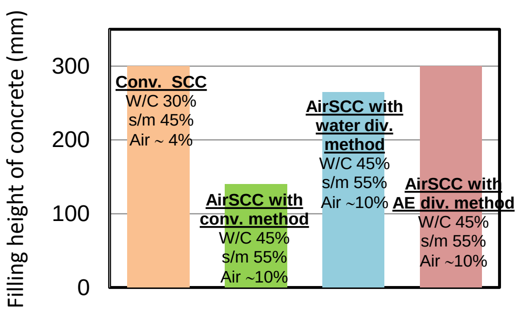

Fig. 18 Filling height of fresh concrete with different mixing method

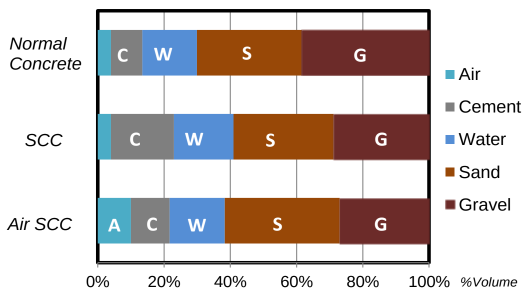

Fig. 19 Volume fraction of materials in concrete

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) 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.

(2) The degree of interaction between model coarse aggregate and mortar (1-$\boldsymbol{R_{mb}/R_m}$) could be used to preliminary evaluate flowability of mortar itself and this index was significantly related to the filling height of concrete box test. Therefore 1-$\boldsymbol{R_{mb}/R_m}$ can be capable of being used for predicting self-compactability of fresh concrete.

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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