Improvement in Self-compacting Properties of Fresh Concrete by Eliminating Large Air Bubbles using an Antifoaming Agent

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Improvement in Self-compacting Properties of Fresh Concrete by Eliminating Large Air Bubbles using an Antifoaming Agent

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Abstract

The effectiveness of two types of procedure for removing large air bubbles in order to increase the percentage of small air bubbles, which is envisaged to be effective for improving the self-compacting properties of fresh concrete, by the addition of an antifoaming agent during mixing has been investigated. In the method of removal using an antifoaming agent after entraining many small air bubbles by divided water mixing, in all the cases investigated, namely adding antifoaming agent at the same time as the primary water, adding antifoaming agent at the same time as the secondary water, and adding antifoaming agent finally, it was not possible to remove large diameter air bubbles, on the contrary they increased. On the other hand, in the method of removing by mixing all together and adding the antifoaming agent finally after a large quantity of air bubbles has been entrained, if the quantity of air entraining agent is increased, the percentage of small diameter bubbles is increased, and the percentage of large diameter bubbles can be reduced.

1. Introduction

About 30 years has passed since the development of self-compacting concrete, but it has not been widely adopted. The authors are undertaking to commercialize bubble lubricated self-compacting concrete in which a portion of the powder in the concrete is replaced with air bubbles to reduce the cement quantity and cost, and the self-compacting properties are similar to those of conventional self-compacting concrete (Attachaiyawuth *et al.* 2015). The authors have found that fine air bubbles are effective in improving the self-compacting properties (Attachaiyawuth *et al.* 2016; Puthipad *et al.* 2016a).

The objective of this research is to efficiently entrain many small size air bubbles (diameter: 0.4 mm or less) in concrete to enable sufficient self-compacting properties to be obtained with a low air content of approximately 5% which is adequate for freezing-thawing resistance (JSCE 1998; Lazniewska-Piekarczyk 2013). For this purpose large diameter air bubbles (diameter: 0.4 mm or more) which are not effective for the self-compacting properties are removed using an antifoaming agent, and the percentage of small diameter air bubbles in the concrete is increased. The antifoaming agent

has an adverse effect on the air bubble distribution, etc. Also, there are reports that its bubble-reducing effect of reducing the fine bubbles entrained with AE agent predominates over its effect of elimination of large air bubbles, which do not contribute to freeze resistance.

The authors have confirmed that the air bubble distribution in concrete can be made finer by adjusting the mixing procedure with the same air content (Attachaiyawuth *et al.* 2016). This is considered to be due to changes in the size of the air bubbles and the surface tension, etc., focusing on the effect on the entrained air bubbles of adjusting the mixing time after addition of the air entraining agent and changing the bubble formation properties by changing the viscosity of the slurry before addition of the air entraining agent (Rath *et al.* 2016). The fine bubbles effective for improving self-compactability could be entrained by specific type of air-entraining agent. Moreover, self-compactability enhancement by ball bearing of fly ash was studied in recent years (Puthipad *et al.* 2016b; Attachaiyawuth and Ouchi 2014). The effectiveness of ball bearing effect of fine bubbles was similar to that of fly ash with the same volume (Puthipad *et al.* 2016b). Accordingly, it is necessary to study various methods including materials used in order to entrain high amount of fine bubbles or to eliminate large bubbles. The starting point for this research was the idea that by adjusting the timing, etc., of addition of antifoaming agent, it is possible to remove large air bubbles which are not effective for the self-compacting properties, and increase the proportion of small air bubbles in the concrete.

2. Test method and conditions

2.1 Test method
The interaction effects when fresh concrete is deformed were quantitatively determined from tests on mortar

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using the "Simple Method of Evaluating the Interaction Effects between Coarse Aggregate and Mortar Particles in Self-compacting Concrete" (Ouchi *et al.* 1999). **Figure 1** shows a mortar funnel test. In this test the mortar funnel velocity ratio (R_m) and the funnel velocity ratio of mortar mixed with glass beads as mock coarse aggregate (R_{mb}) are measured, and the degree of reduction ($1 - R_{mb}/R_m$) in the deformability of the mortar phase when the concrete is deforming is quantitatively determined. The tested funnel velocity, R_m and R_{mb} were calculated using down flow time of mortar shown in **Fig. 1**. Those two indexes were manipulated to the degree of reduction in deformability of mortar ($1 - R_{mb}/R_m$). This index was the relative reduction in funnel velocity of mortar due to the presence of glass beads, which indicated degree of internal friction of mortar as shown in **Fig. 2**. At the bottleneck of the funnel during the test, mortar was compressed by the approaching of glass beads (σ), which resulted in the increase in mortar's shear resistance (τ). High shear resistance meant high internal friction, which corresponded to low funnel velocity (R_{mb}) because of the increase in the down flow time of mortar (t_m). The $1 - R_{mb}/R_m$ increased corresponding to the increase in the internal friction, which indicated the reduction in flowability of mortar. Accordingly, the high flowability mortar should possess low internal friction represented by the low value of the tested $1 - R_{mb}/R_m$. The test items carried out were tests for the fresh properties using mortar flow tests, air content tests (mass method), and the mortar funnel test. Also, the air bubbles and air bubble distribution were measured on hardened test specimens. The tests after hardening determined the distribution of air bubble size by the linear traverse method in accordance with ASTM C 457-09 (ASTM 2009). Moreover, this test provided a useful index indicating fineness of air bubbles called specific
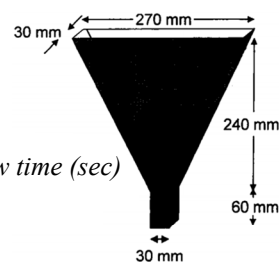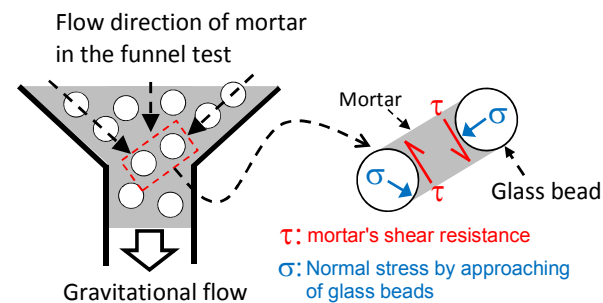
surface area (α), which automatically obtained from the test. It was calculated by a total measured surface area of bubbles divided by a total measured volume of bubbles in each specimen. Thus, the unit of this index is bubbles surface area/bubbles volume (mm^2/mm^3). Higher value of α indicates finer air bubbles. Also, cylindrical test specimens of diameter 100 mm and height 200 mm were used. Test specimens of about 50 mm thickness were cut from about 10 mm inside the top and bottom surfaces, and from the center in that order, to obtain top, middle, and bottom test specimens, and the measurements averaged from the top and bottom of each of these test specimens were taken to be one case.

2.2 Outline of tests

Table 1 shows the list of test cases. Antifoaming agent was tested with both divided water mixing and mixing all together. **Figure 3** shows the mixing procedures. Tests were carried out with divided water mixing increasing the percentage of small air bubbles, then removing air bubbles with antifoaming agent (Series 1), and with mixing all together entraining a large amount of air bubbles then removing the air bubbles with the antifoaming agent after (Series 2 to 4). The antifoaming agent may have an inverse effect with air entraining

Fig. 1 Mortar funnel test.

Funnel velocity ratio
R_m, R_{mb} = 10/down flow time (sec)

Fig. 2 Internal friction of mortar due to glass beads in funnel test.

Fig. 3 Mixing procedures (a: Series 1, b: Series 2-4).

Table 1 Test cases.

Series	Item investigated		Mixing procedure Timing of addition	Cement	Fine aggregate	High-range water reducer	AE agent	Antifoaming agent
1	Investigation of divided water mixing	Effect of timing of addition of anti-foaming agent	Divided water mixing + no antifoaming agent	OPC	S1	SP1	AE1	D
			Divided water mixing + early antifoaming agent addition					
			Divided water mixing + intermediate antifoaming agent addition					
			Divided water mixing + late antifoaming agent addition					
2	Investigation of mixing all together	Effect of quantity of AE agent	Mixing all together + late antifoaming agent addition					
3		Comparison of mixing procedures	Mixing all together + late antifoaming agent addition		S1, S2			
			Divided water mixing + no antifoaming					
			Mixing all together + no antifoaming agent					
4		Comparison of mixing procedures	Mixing all together + late antifoaming agent addition		S2		AE2	
			Divided water mixing + no antifoaming agent					
			Mixing all together + no antifoaming agent					

agent, thus this bubbles remover may have different effect on air entrainment due to timing of addition. High volume of small air bubbles might be entrained if the antifoaming agent is added earlier, or those two agents are added at the same time because large bubbles might be eliminated during mixing. On the other hand, after process of air entrainment, only large bubbles might be eliminated by adding antifoaming agent after mixing mortar with air entraining agent. Therefore, this timing adjustment of antifoaming addition may affect bubbles size distribution of entrained air. In series 1, timing of adding antifoaming agent was studied by 3 cases, (1) adding the antifoaming agent at the same time as the primary water (before adding air entraining agent), (2) adding the antifoaming agent at the same time as the secondary water (at the same as adding air entraining agent), and (3) adding the antifoaming agent at the end (after adding air entraining agent). Effectiveness of anti-foaming agent on the elimination of large bubbles might be differed according to the timing of addition.

2.3 Materials used
The cement used was ordinary Portland cement (OPC,

density: 3.15 g/cm^3), and the fine aggregate used was Sanokuni hard sandstone from Kochi Prefecture (sur-face dried density: 2.695 g/cm^3, S1: FM2.58, S2: FM2.53). One type of high performance AE water re-ducing agent was used (polycarbonate ester compound and intramolecular crosslinked polymer complex SP). Two types of air entraining agent were used (natural resinate AE1 and an alkyl ester negative ion surfactant AE2). One type of antifoaming agent was used (polyal-kylene glycol derivative D).

2.4 Mixes
The volume percentage of fine aggregate in the mortar excluding air (s/m) was set at 55%, and the water ce-ment ratio (W/C) at 45%. The air bubble lubricated self-compacting concrete that was the subject of this re-search requires sufficient deformability, so the quantity of high-range water reducer added was adjusted so that the mortar slump flow was about 250-270 mm. The quantity of antifoaming agent was adjusted so as to ob-tain an air content of 7% in the target mortar. **Table 2** shows the specified mix proportions.

Table 2 Specified mix proportions of the bubble lubricated self-compacting mortar (excluding air).

Unit mass (kg/m³)			
W	C	S	SP
264	586	1480	8.2-16.4

*SP: The detailed quantities are given in each section

3. Divided water mixing

The percentage of small air bubbles is increased by divided water mixing, so the effect on the air bubble size distribution due to the removal of air bubbles with antifoaming agent and the timing of the addition of the antifoaming agent was investigated. **Table 3** shows the quantities of the admixtures used. **Table 4** shows the tested fundamental fresh properties of mortar. **Figure 4** shows the relationship between the air content and 1-R_{mb}/R_m. The friction between the solid particles of the mortar for divided water mixing with no antifoaming agent added with about 10% air content was low. However, when antifoaming agent was added and air bubbles removed, the friction between the solid particles of the mortar was increased for all of early antifoaming agent addition, intermediate antifoaming agent addition, and late antifoaming agent addition.

The air bubble distribution in the test specimens after hardening was investigated. **Figure 5** shows the volume of air for each bubble diameter. When no antifoaming agent was added the small air bubbles were about 10% and the large air bubbles were less than 1%. However when antifoaming agent was added, the quantity of
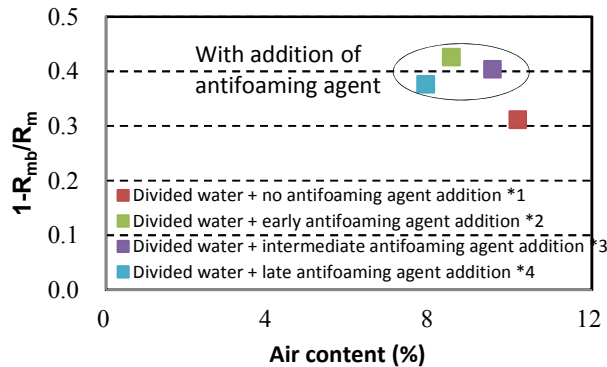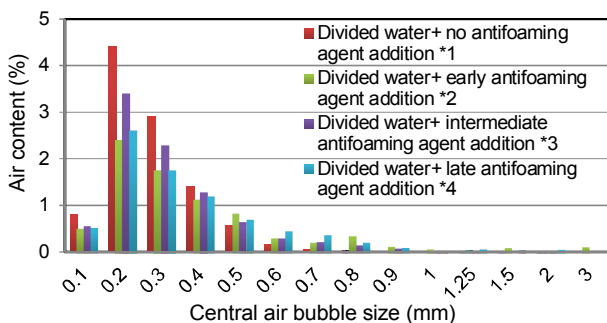
Table 3 Quantities of admixtures (Series 1).

	Quantity of high-range water reducer (C×%)	Quantity of air entraining agent (C×%)	Quantity of antifoaming agent (C×%)
*1	2.6	0.4	-
*2			0.02
*3			
*4			

*C×1.0% is 5.86 kg/m³ (likewise hereafter)

Table 4 Tested fundamental fresh properties of mortar (Series 1).

	Average flow diameter (mm)	Air content (%)	R_m	R_{mb}	1-R_{mb}/R_m
*1	252	10.2	2.21	1.52	0.312
*2	260	8.5	2.38	1.37	0.424
*3	255	9.6	2.28	1.36	0.404
*4	261	7.9	2.54	1.58	0.378

small air bubbles was reduced. On the other hand the quantity of large air bubbles increased. It was unexpected phenomena because large bubbles possessing unbeneficial property for self-compactability were expected to be eliminated. Very small volume of large bubbles were entrained even without antifoaming agent (*1), thus small bubbles were inevitably eliminated by antifoaming agent (*2, *3, *4). However, large bubbles were slightly observed even the antifoaming agent was added. The portion of large bubbles was slightly produced during the process of mixing mortar with the antifoaming agent, which air entrainment by air entraining agent was more effective than the air elimination by antifoaming agent.

Figure 6 shows the change in air content for each bubble size relative to no antifoaming agent addition as

Fig. 4 Relationship between air content and 1-R_{mb}/R_m (Series 1).
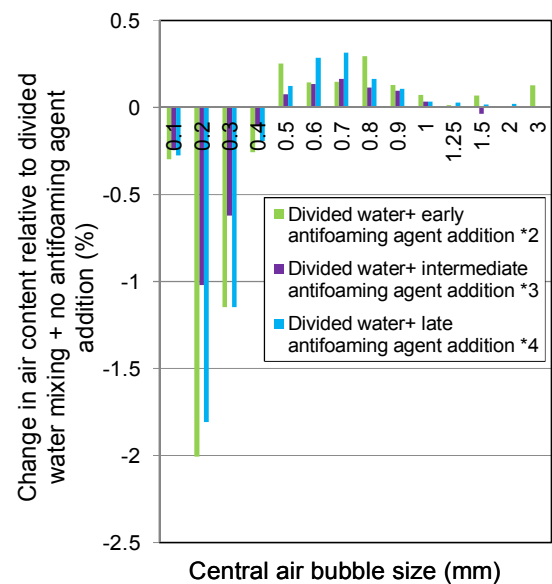
Fig. 5 Air volume at each bubble size (Series 1).

Fig. 6 Change in air content at each air bubble size relative to divided water mixing + no antifoaming agent addition (Series 1).

Table 5 Quantities of admixtures (Series 2).

	Quantity of high-range water reducer (C×%)	Quantity of air entraining agent (C×%)	Quantity of antifoaming agent (C×%)
*5	1.9	0.08	0.0004
*6			0.0006
*7	2.2	0.20	0.0150
*8	2.2		0.0200
*9	2.1		0.0250
*10	2.0		0.0300
*11	2.6	0.60	0.0500
*12	2.6		0.0700
*13	2.6		0.0800

Table 6 Tested fundamental fresh properties of mortar (Series 2).

	Average flow diameter (mm)	Air content (%)	R_m	R_{mb}	$1-R_{mb}/R_m$
*5	258	7.2	1.82	1.05	0.423
*6	268	10.6	1.83	*stopped	1.000
*7	266	10.1	1.92	1.04	0.458
*8	273	7.2	1.96	1.00	0.490
*9	268	6.3	1.85	0.88	0.524
*10	259	4.6	1.78	0.82	0.539
*11	243	13.2	1.72	0.95	0.448
*12	250	8.1	1.77	1.05	0.407
*13	258	6.5	1.91	1.18	0.382

standard. The results show that although when antifoaming agent is not added, the total of large size bubbles is less than 1%, for early antifoaming agent addition, intermediate antifoaming agent addition, and late antifoaming agent addition there was an increase of about 2% in all cases. With no addition of antifoaming agent the total of small bubbles was nearly 9%, but for early antifoaming agent addition, intermediate antifoaming agent addition, and late antifoaming agent addition there was a decrease of about 6% in all cases.

Figure 7 shows the specific surface areas in each test. The value of specific surface area was largest for no addition of antifoaming agent. The air bubbles can be said to have become finer. When antifoaming agent was added the value of specific surface area was reduced in all cases of early antifoaming agent addition, intermediate antifoaming agent addition, and late antifoaming agent addition, so it can be seen that the bubble size became coarser.

With the divided water mixing method, it was confirmed that the air content was reduced by the effect of the antifoaming agent. Conversely however, for each of early antifoaming agent addition, intermediate antifoaming agent addition, and late antifoaming agent addition, the friction between the solid particles of the mortar increased. It was confirmed that the percentage of large bubbles increased, and the percentage of small bubbles decreased.

With the addition of antifoaming agent in this section it can be said that it was not possible to achieve the ob-
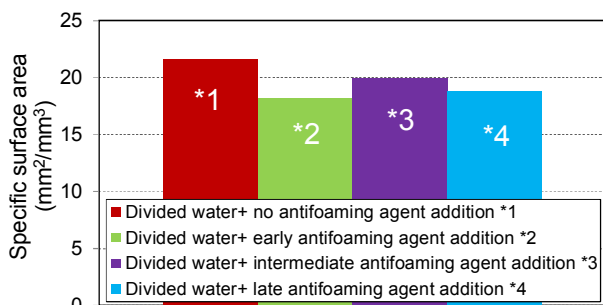
jective. To achieve high volume of small bubbles with low volume of large bubbles, the antifoaming agent was not necessary at any timing addition because the divided water mixing method itself could provide the expected bubbles size distribution (high volume of small bubbles with low volume of large bubbles). This result corresponded to the previous studied that small bubbles were effectively entrained with very small volume of large bubbles by making mortar portion slightly wet before adding air entraining agent, which could be provided by the divided water mixing method (Attachaiyawuth *et al*. 2016).

4. Mixing all together

4.1 Effect of increasing quantity of antifoaming agent

With mixing all together the method of removal using antifoaming agent after a large quantity of air bubbles was entrained was investigated. **Table 5** shows the quantity of admixtures added and **Table 6** shows the tested fundamental fresh properties of mortar. **Fig. 8** shows the relationship between the air content and $1-R_{mb}/R_m$. In the case of *5 and *6 which had the lowest quantity of air entraining agent, with the addition of antifoaming agent the friction between solid particles of the mortar increased greatly, and the funnel was blocked. In the cases of *7 to *9, the friction between solid particles of the mortar increased gradually with the addition
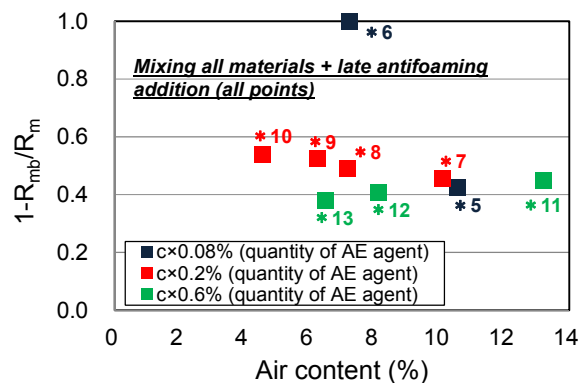

Fig. 7 Effect of timing of antifoaming agent addition on specific surface area (Series 1).

Fig. 8 Relationship between air content and 1-Rmb/Rm (Series 2).

Table 7 Quantities of admixtures (Series 3, S1).

	Quantity of high-range water reducer (C×%)	Quantity of air entraining agent (C×%)	Quantity of antifoaming agent (C×%)
*14			0.050
*15	2.50	0.600	0.065
*16			0.080
*17	2.30	0.440	
*18	1.50	0.088	
*19	1.40	0.040	
*20	1.65	0.068	-
*21	1.60	0.052	
*22	1.55	0.040	

Table 9 Quantities of admixtures (Series 3, S2).

	Quantity of high-range water reducer (C×%)	Quantity of air entraining agent (C×%)	Quantity of antifoaming agent (C×%)
*23	2.8	0.200	0.02
*24	2.6	0.064	-
*25	2.1	0.068	

Table 8 Tested fundamental fresh properties of mortar (Series 3, S1).

	Average flow diameter (mm)	Air content (%)	R_m	R_{mb}	$1-R_{mb}/R_m$
*14	244	13.3	1.61	0.92	0.429
*15	254	9.5	1.74	1.06	0.391
*16	263	6.6	1.76	1.07	0.392
*17	252	13.7	1.98	1.22	0.384
*18	255	10.2	2.37	1.34	0.435
*19	249	7.5	2.21	1.16	0.475
*20	251	13.8	1.91	1.12	0.414
*21	256	10.0	1.81	1.06	0.414
*22	258	6.9	1.75	0.98	0.440

Table 10 Tested fundamental fresh properties of mortar (Series 3, S2).

	Average flow diameter (mm)	Air content (%)	R_m	R_{mb}	$1-R_{mb}/R_m$
*23	254	7.3	1.49	0.99	0.336
*24	255	7.4	1.66	0.98	0.410
*25	254	8.0	1.66	0.97	0.416

of antifoaming agent. With *11 and *12 which had the largest quantity of air entraining agent, the friction between solid particles of the mortar reduced with the addition of antifoaming agent.

4.2 Effect of large quantity of air entraining agent and comparison with divided water mixing

For comparison with mixes without addition of antifoaming agent, tests were carried out with mixing all together + no antifoaming agent addition and divided water mixing + no antifoaming agent addition. **Table 7** shows the quantities of admixtures used and **Table 8** shows the tested fundamental fresh properties of mortar. **Figure 9** shows the relationship between the air content and $1-R_{mb}/R_m$. As the air content was increased with mixing all together + no antifoaming agent addition and divided water mixing + no antifoaming agent addition, the friction between solid particles of the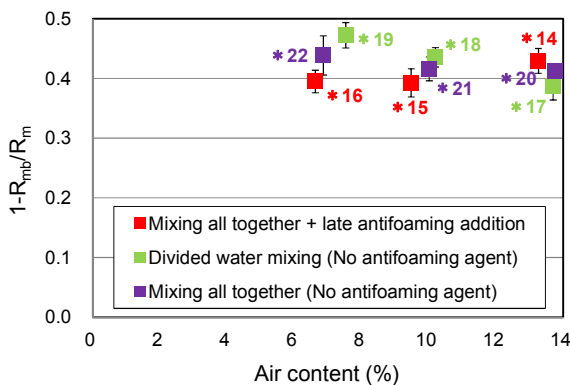 mortar decreased. When the quantity of antifoaming agent increased in mixing all together + late antifoaming agent addition, the friction between solid particles of the mortar decreased as the air content was reduced.

Also, a test was carried out in which the particle size distribution of the fine aggregate was changed. **Table 9** shows the quantity of admixtures used and **Table 10** shows the tested fundamental fresh properties of mortar. **Figure 10** shows the relationship between the air content and $1-R_{mb}/R_m$. Further reduction in the friction was achieved by changing the particle size distribution of the fine aggregate. The fine particles in the size range 0.15 to 0.6 mm were increased, so it is considered that a large quantity of small air bubbles was entrained.

4.3 Effect of changing the air entraining agent

The type of air entraining agent was changed, and the tests as described previously were carried out. **Table 11** shows the quantities of admixtures used and **Table 12**
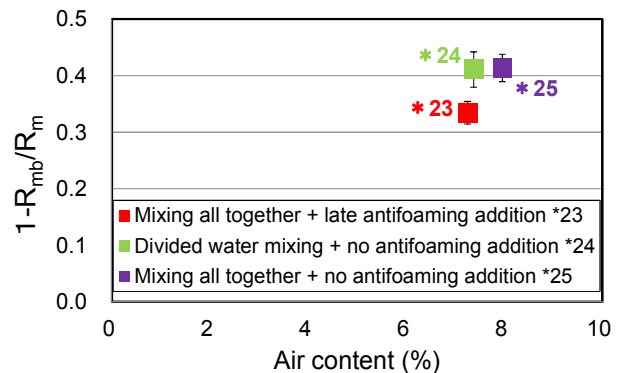

Fig. 9 Relationship between air content and $1-R_{mb}/R_m$ (Series 3, S1).

Fig. 10 Relationship between air content and $1-R_{mb}/R_m$ (Series 3, S2).

Table 11 Quantities of admixtures (Series 4, S2).

	Quantity of high-range water reducer (C×%)	Quantity of air entraining agent (C×%)	Quantity of antifoaming agent (C×%)
*26	2.3	0.0200	0.040
*27	2.4	0.0400	0.065
*28	2.4	0.0650	
*29	2.7	0.0150	-
*30	2.1	0.0045	

Table 12 Tested fundamental fresh properties of mortar (Series 3, S2).

	Average flow diameter (mm)	Air content (%)	R_m	R_{mb}	$1-R_{mb}/R_m$
*26	260	7.4	1.70	0.96	0.435
*27	255	7.3	1.68	1.06	0.369
*28	247	7.3	1.61	1.04	0.354
*29	253	6.8	1.89	1.19	0.370
*30	251	7.3	1.57	0.83	0.471

shows the tested fundamental fresh properties of mortar. **Figure 11** shows the relationship between the air content and $1-R_{mb}/R_m$. Here also the quantity of air entraining agent initially added was increased in the order *26, *27, *28. In the case of mixing all together + late antifoaming addition, as the quantity of air entraining agent was increased, the friction between solid particles of the

mortar was reduced, the same as previously.

Next, **Fig. 12** shows a graph of specific surfaces areas, showing the air bubbles after hardening. **Figure 13** shows the volume percentages of the air bubble sizes. **Figures 14** and **15** show the air volume at each air bubble size. In the case of mixing all together + no antifoaming agent addition, the value of specific surface area was small, close to about 3% of large air bubbles remained, and the air bubble sizes were large compared with the others. On the other hand, with mixing all together + late antifoaming agent addition, the specific surface area increased as the quantity of air entraining agent was increased, and the large size air bubbles were reduced to about 2%. As the quantity of air entraining agent was increased, the volume percentage of small air bubbles increased, so the air bubble size decreased.

In the case of mixing all together + late antifoaming agent addition, the air bubble size reduced as the quantity of air entraining agent was increased. However, it
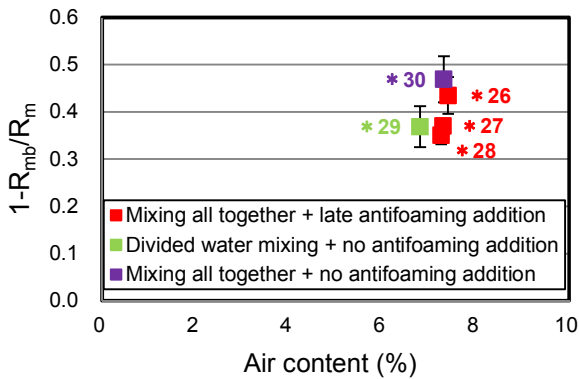

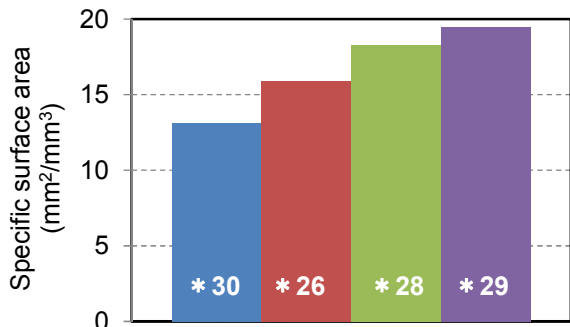Fig. 11 Relationship between air content and $1-R_{mb}/R_m$ (Series 4).

Fig. 12 Specific surface area (Series 4).

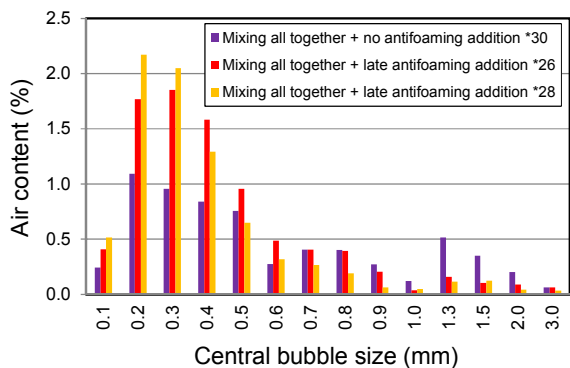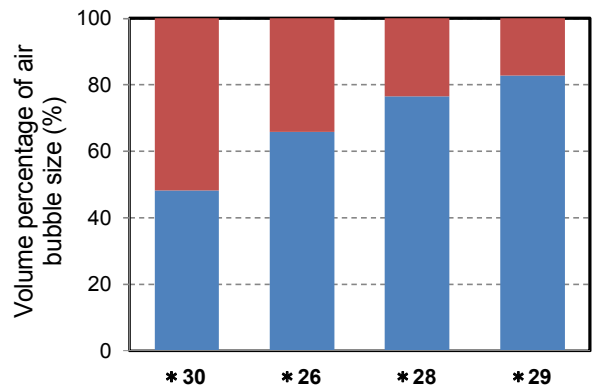Fig. 14 Air volume at each bubble size (Series 4).

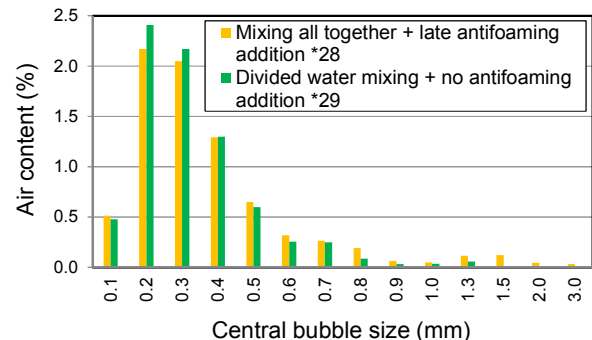Fig. 13 Volume percentage of air bubbles (Series 4).

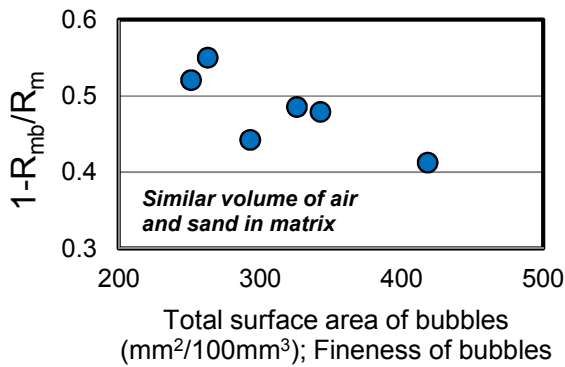Fig. 15 Air volume at each bubble size (Series 4).

Fig. 16 internal friction of mortar affected by fineness of entrained bubbles (Attachaiyawuth *et al*. 2016).
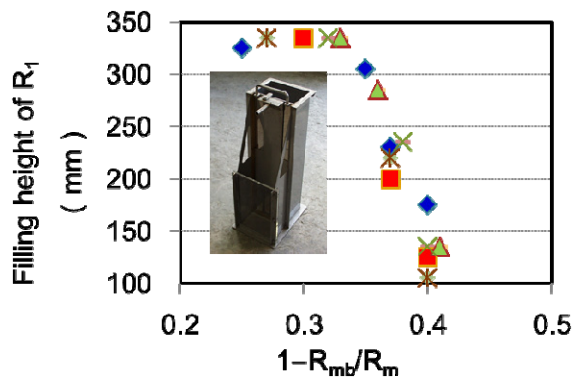

Fig. 17 Relationship between self-compactability of concrete and internal friction of mortar (Okamura and Ouchi 2003).

was not possible to reduce the air bubble size down to that of divided water mixing + no antifoaming agent addition. The percentage of large air bubbles was smallest for divided water mixing + no antifoaming agent addition at about 1%, and the value of specific surface area was small, so the volume percentage of small air bubbles was highest compared with the others.

The technique of increasing small bubbles by increasing air entraining agent can be practically applied to self-compacting concrete technology in order increase self-compactability. It has been reported that fineness of entrained bubbles represented by total surface area (similar air volume) significantly affected the friction index of mortar ($1-R_{mb}/R_m$) as shown in **Fig. 16** (Attachaiyawuth *et al.* 2016). The $1-R_{mb}/R_m$ reduced with the increase of fineness of bubbles. When mortar mixes with various $1-R_{mb}/R_m$s were applied to concrete mixes, there has been a good relationship between $1-R_{mb}/R_m$ and fill height of concrete as shown in **Fig. 17** (Okamura and Ouchi 2003). It can be said that the increasing volume of small bubbles by the procedures studied in this work can be applied to self-compacting concrete technology in order to increase the self-compactability.

5. Conclusions

In this research two methods of eliminating large air bubbles using antifoaming agent were investigated in order to increase the percentage of small air bubbles, which is envisaged to be comparatively advantageous for the self-compacting properties. The first method was to carry out the elimination process after entraining air bubbles that were as fine as possible, in divided water mixing. The second method was to carry out the elimination process after entraining a large quantity of air bubbles in mixing all together.

The following are the conclusions from this research.

(1) In the method of reducing the quantity of air bubbles by adding the antifoaming agent to mortar having about 10% air content with divided water mixing, the air content was reduced in all three cases, (1) adding the antifoaming agent at the same time as the primary water, (2) adding the antifoaming agent at the same time as the secondary water, and (3) adding the antifoaming agent at the end. However, the result was the quantity of small air bubbles was reduced, and the quantity of large air bubbles was increased. Addition of antifoaming agent eliminated the fine air bubbles rather than eliminating the large air bubbles. The antifoaming agent was not necessary at any timing addition because the divided water mixing itself could entrain high volume of small bubbles and very low volume of large bubbles.

(2) With the conventional method of mixing the mortar all together and adding the air entraining agent at the same time, the percentage of small air bubbles was low and the percentage of large air bubbles was high. With the method of adding the antifoaming agent after mixing all together which was studied in this research, if the quantity of initially added air entraining agent was small, the friction between solid particles of mortar increased in accordance with the reduction in air content. On the other hand, as the quantity of air entraining agent used was increased, the friction between the solid particles of the mortar gradually reduced. In this case, it was confirmed from the air bubble distribution after hardening that the percentage of small air bubbles was increased and the percentage of large air bubbles was decreased. This technique can be practically applied to self-compacting concrete technology in order to reduce internal friction of mortar, which directly improves the self-compactability of fresh self-compacting concrete.

(3) With the method of mixing the mortar all together and finally adding the antifoaming agent which was studied in this research, the percentage of small air bubbles was increased and the percentage of large air bubbles was reduced. However, it was confirmed that the air bubble distribution was finer with the method of divided water mixing the mortar.

A task for future investigation is the effect of the type of admixture.

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