Journal of Advanced Concrete Technology
Materials, Structures and Environment

Improvement of Self-Compactability of Air-Enhanced Self-Compacting Concrete with Finer Entrained Air

Anuwat Attachaiyawuth, Sovannsathya Rath, Kazunori Tanaka, Masahiro Ouchi

Journal of Advanced Concrete Technology, volume 14 (2016), pp. 55-69

Scientific paper

Improvement of Self-Compactability of Air-Enhanced Self-Compacting Concrete with Fine Entrained Air

Anuwat Attachaiyawuth[1*], Sovannsathya Rath[2], Kazunori Tanaka[3] and Masahiro Ouchi[4*]

Received 3 September 2015, accepted 23 February 2016 doi:10.3151/jact.14.55

Abstract

The purpose of this study is to clarify the enhancement in self-compactability of self-compacting concrete with entrained air with respect to the size of entrained air bubbles. Air bubbles entrained with a simple mixing method in which all the materials were poured at once was not suitable for enhancement in self-compactability. The authors developed a new mixing method called water-dividing mixing method, which enabled entrained air bubbles to be suitable for enhancement in self-compactability. The water-dividing method with excessive dosage of air entraining agent (AE) entrained high proportion of smaller air bubbles. The larger total surface area of bubbles due to high amount of fine entrained air reduced internal friction of fresh mortar during deformation, resulted in higher level of self-compactability of self-compacting concrete. This usefulness leads to the successful achievement of self-compacting concrete (SCC) with lower cement content with the air content of approximately 10%. The authors have named the concrete "air-enhanced self-compacting concrete (air-SCC)."

1. Necessity for low cement content with maintaining level of self-compactability and air-Enhancement for lower cement content and higher aggregate content

Self-compacting concrete (SCC) was first developed in Japan in 1988 in order to improve durability of concrete structures (Okamura *et al.* 1993). It is usually well-known treated as high performance concrete that can flow into every corners of formwork by its own weight without any vibration. However, SCC has not been extensively used because of its high cost due to high unit cement content.

According to "JSCE Recommendation for Self-Compacting Concrete" (JSCE 1999), the water to binder ratio (W/B) in conventional SCC is recommended to be in the range of 28-33% by weight in order to ensure that segregation will not occur. Sand to mortar ratio (s/m) is also limited approximately at 45% by volume. The self-compactability of SCC is very sensitive to the unit volume of coarse aggregate in the mix. Accordingly, the volume of coarse aggregate is recommended as approximately in the range of 30-33%. According to the limitation of materials amount used for SCC mentioned previously, high amount of cement is necessary to achieve SCC with sufficient self-compactability.

The unit cement content in SCC is approximately 2 times higher than that of ordinary concrete and aggregate content is lower than that of ordinary concrete, as shown in **Fig. 1**. Moreover, low-heat cement which is not so common in the market is necessary for SCC if cement is to be used as the only powder material in SCC. This results in high unit cost of SCC. SCC has been mostly used in structures with a confined zone of reinforcing bars, to which vibrating compaction is difficult or impossible.

The authors have proposed an Air-enhanced Self-Compacting Concrete (air-SCC) based on a concept in which self-compactability of SCC can be enhanced by entraining air. Specific gravity of air-SCC significantly depends on air content, especially for air-SCC includes air content of 5 to 20%. Self-compactability seems to reduce when the specific gravity reduces due to the reduction of its gravity force (self-weight). On the contrary, air-SCC with air content of 10% exhibited high self-compactability evaluated according to Japanese standard. The suitable quality of entrained air which enables fine aggregate content in the mortar can be increased resulting in a reduction in cement content lead-

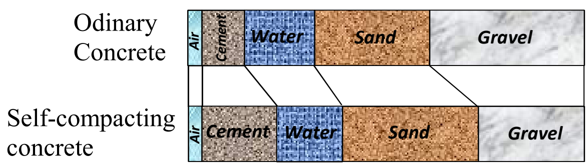


Fig. 1 High amount of cement needed for SCC (Okamura et al. 1993).

[1]Postdoctral researcher, Department of Infrastructure Systems Engineering, Kochi University of Technology, Kami-city, Kochi Pref., Japan. *Corresponding author, *E-mail:* anuwat.atta@gmail.com
[2]PhD candidate, Department of Infrastructure Systems Engineering, Kochi University of Technology, Kami-city, Kochi Pref., Japan.
[3]Engineer, Giken Ltd., Tokyo, Japan.
[4]Professor, Department of Infrastructure Systems Engineering, Kochi University of Technology, Kami-city, Kochi Pref., Japan. *Corresponding author, *E-mail:* ouchi.masahiro@kochi-tech.ac.jp

ing to a reduction in the unit cost of SCC. The concept of air-SCC was summarized in **Fig. 2**. Effective entrained air produced by effective mixing method enhances flowability by trundling sand particles in mortar matrix resulting in flowability enhancement of mortar as shown in **Fig. 3**.

Air-SCC is expected to be used for ordinary reinforced concrete structures requiring normal strength. The level of self-compactability at fresh state has to be kept as that of the conventional SCC. The target compressive strength of air-SCC is similar to that of ordinary concrete of 30N/mm^2. Small air bubbles have been normally entrained into concrete for achieving freezing and thawing resistance of concrete in the cold environment.

2. Simple test method for friction in mortar during deformation of SCC in fresh state

For developing air-SCC, the degree of friction obtained from standard testing method of mortar was used as an index for evaluating flowability of mortar. Glass bead with 10mm in diameter was used as model coarse aggregate in order to evaluate shear resistance of mortar due to normal stress by the approaching of real coarse aggregate during concrete deformation as shown in **Fig. 4**. 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 represents self-compactability of fresh concrete.

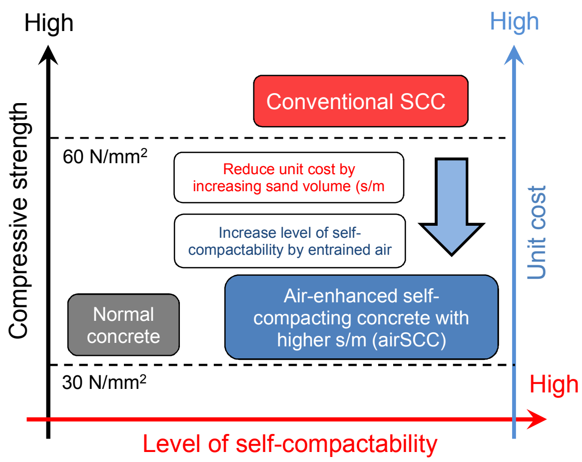


Fig. 2 Concept of the development of air-SCC.

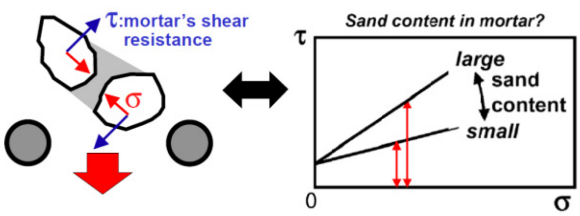


Fig. 4 Shear resistance of mortar (τ) in accordance with normal stress (σ) (Okamura *et al*. 1993).

The degree of friction caused by model aggregate approaching in mortar is represented as ($1-R_{mb}/R_m$) obtained from the tested funnel speeds of mortar (R_m) and mortar with model coarse aggregate (R_{mb}). R_m and R_{mb} are defined in equation (1) and (2), respectively, which are obtained from mortar funnel test (Okamura and Ozawa 1995), as shown in **Fig. 5**. Finally, the interaction between model coarse aggregate and mortar ($1-R_{mb}/R_m$) could be used as the preliminary index for evaluating the appropriacy of 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

The index $1-R_{mb}/R_m$ is 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** (Okamura and Ouchi 2003). Therefore the index of ($1-R_{mb}/R_m$) is capable to be used to preliminary evaluate self-compactability of fresh concrete.

3. Reduction in friction of mortar by air entrained with simple mixing method

The purpose of entraining air in this research was to reduce friction in mortar in SCC in fresh state during deformation. The effect of entrained air on reduction in friction was plainly explained by "Ball-bearing effect" in which entrained air bubbles in mortar matrix behave

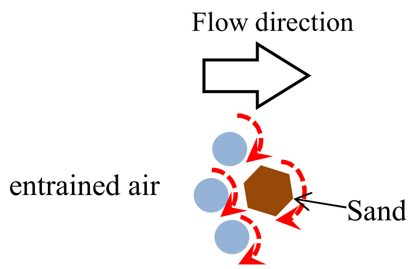


Fig. 3 Entrained bubbles enhance flowability of mortar.

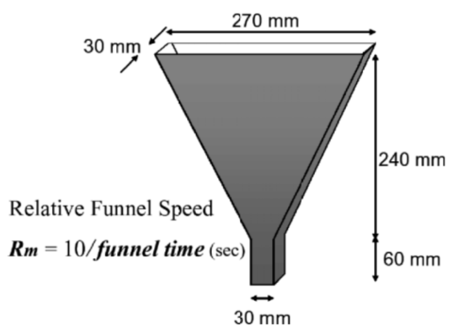


Fig. 5 Mortar funnel test (Okamura and Ozawa 1995).

like ball bearing to solid particles by trundling, as shown in **Fig. 7** (Attachaiyawuth and Ouchi 2014).

The reduction in the funnel speed of mortar with glass beads (ΔR_{mb}) due to entrained air was employed as an index for effect of entrained air on the flowabiltiy of glass beads in mortar. This reduction means the mitigation in reduction of R_{mb} by entrained air which was calculated from the difference of R_{mb} between mortar with entrained air and without entrained air. Once entrained air was incorporated into the mortar, there were two effects affecting R_{mb} which were water retention and ball bearing effect. Water retention reduced R_{mb} because of the loss of free water and ball bearing effect increased R_{mb} because of flowability enhancement. The combination of those two effects caused the different value of (ΔR_{mb}). This reduction in R_{mb} (ΔR_{mb}) represented flowability of mortar that low reduction in R_{mb} is equivalent to high flowability of glass beads. On the other hand, high reduction of R_{mb} is equivalent to low flowability of glass beads as shown **Fig. 8**.

Air entraining agent is liquid material, thus it is added to mix proportion concurrently with water and superplasticizer. Cementitious materials is ordinary portland cement. Fine aggregate is crushed limestone sand which is produced in Japan. In fact, air bubbles become stronger in terms of resistance to collapse due to compression force by aggregate during concrete flow when viscosity of mortar increase. Therefore a new type of superplasticizer (SP2) which is a superplasticizer blended with a viscosity agent was introduced for increasing viscosity of mortar. However, a conventional superplasticizer (SP1) was still used for comparison in this series. Materials in use are listed in **Table 1**.

To clearly compare ball bearing effect by entrained air, sand to mortar ratio (s/m including air) was kept similar for all tested mixtures. The target s/m including air was 45% and 49%. In fact, s/m including air could not be exactly the same as target amount because air content was very sensitive to mix proportion. It could not be fixed at a certain number but was slightly different from the target amount.

Figure 9 a) shows the tested funnel speed of mortar with glass beads (R_{mb}) of mortar using conventional superplasticizer. It can be seen that R_{mb} slightly reduced due to entrained air in mortar with s/m of approximately 45%. This reduction was affected by water retention by entrained air. Although, ball bearing effect by entrained air could increase funnel speed, it's not sufficient to overcome water retention. On the other hand, R_{mb} slightly increased in mortar with s/m of approximately 49%. In this case, ball bearing effect overcame water retention by entrained air resulting in higher funnel speed. **Figure 9 b)** shows the reduction of funnel speed of mortar with glass beads due to the presence of entrained air (ΔR_{mb}). It was calculated by the different value between R_{mb} of mortar with entrained air and mortar without entrained air. In fact, funnel speed of mortar with glass beads (R_{mb}) significantly reduced due to the presence of entrained air because of water retention effect. This resulted in the reduction of funnel speed of mortar. Accordingly, the reduction of R_{mb} due to en-

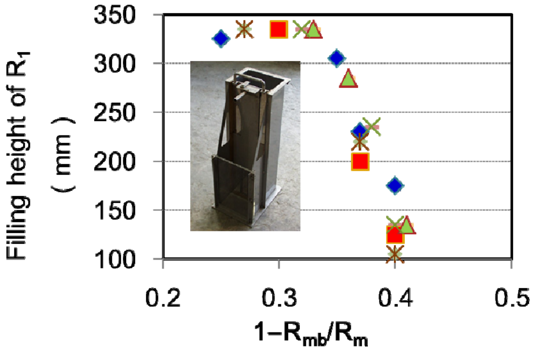


Fig. 6 Relationship between 1-R_{mb}/R_m and filling height of concrete box test (Okamura and Ouchi 2003).

Table 1 Materials used in this study.

Material	Details
Cement	Ordinary portland cement (3.15 g/cm^3)
Fine aggregate	Crushed limestone sand (2.68 g/cm^3, F.M. 2.72)
Model coarse aggregate	Glass beads (2.55 g/cm^3, uniform diameter of 10 mm.)
SP1	Conventional type of superplasticizer (1.044 g/cm^3)
SP2	New type of superplasticizer (1.044 g/cm^3)
AE	Alkyl ether-based anionic surfactants

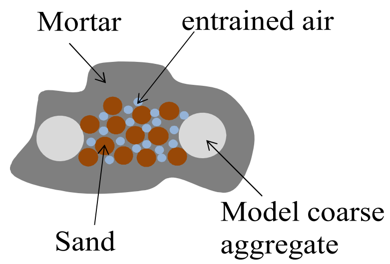


Fig. 7 Ball bearing effect by entrained air (Attachaiyawuth and Ouchi 2014).

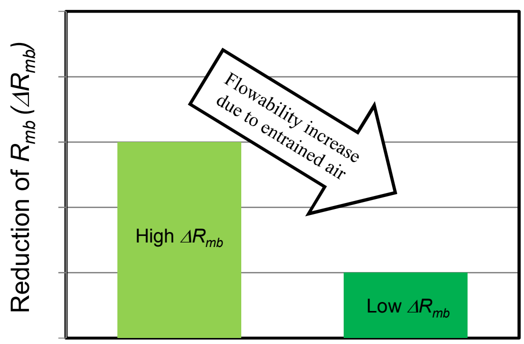


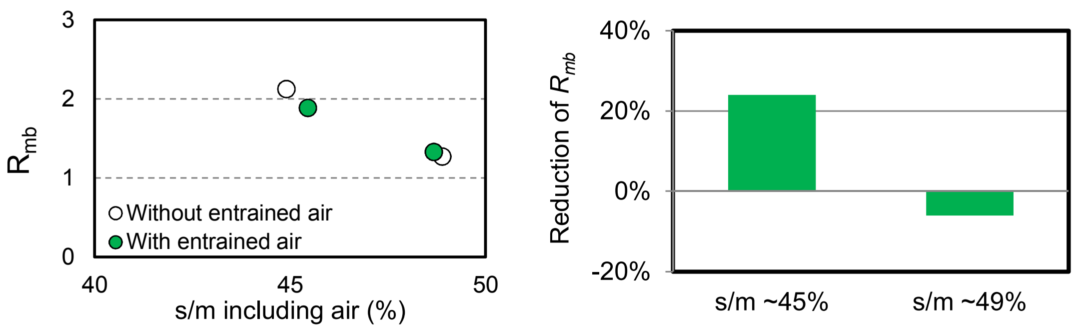
Fig. 8 Reduction of R_{mb} of mortar due to entrained air.

trained air represents the effectiveness of entrained air on flowability of glass beads in mortar. Low reduction of R_{mb} means effective entrained air. There were 2 types of mortar which were mortars with s/m including air of approximately 45% and 49%. It can be seen in **Fig. 9 b)** that the reduction of R_{mb} was not high which was approximately 24% and -6% of mortar with s/m including air of approximately 45% and 49%, respectively. This means that entrained air was effective for enhancing flowability of glass beads. In case of mortar using conventional superplasticizer, it can be said that entrained bubbles was effective for increasing flowability of glass beads in mortar with low and high s/m.

The R_{mb} and ΔR_{mb} regarding s/m including air of mortar using new type of superplasticizer are shown in **Figs. 10 a)** and **10 b)**, respectively. Mortar with s/m of 49% exhibited lower funnel speed (R_{mb}) than that of mortar with s/m of 49% due to high amount of solid particles in matrix. R_{mb} slightly reduced due to the presence of entrained air in mortar with s/m of approximately 45% because of effective ball bearing effect as shown in **Fig. 10 a)**. On the contrary, it apparently reduced in mortar with s/m of approximately 49%. Entrained air was not efffective in mortar with high s/m (49%) and water retention reduced funnel speed due to the loss of water inside mortar matrix. The reduction of R_{mb} of mortar using new type of superplasticizer is shown in **Fig. 10 b)**. In case of mortar with s/m including air approximately 45%, the reduction of R_{mb} was low which was approximately 7%. Entrained air was effective for enhancing flowability of glass beads in mortar with low s/m. In case of mortar with s/m including air approximately 49%, the reduction of R_{mb} was very high which was approximately 76%. Therefore, entrained air produced in mortar with new type of superplasticizer was not suitable for enhancing flowbility of mortar with high s/m (s/m~49%) because mortar became high viscous due to viscosity agent in superplasticizer and short distance between sand particles resulting in ineffective entrained air.

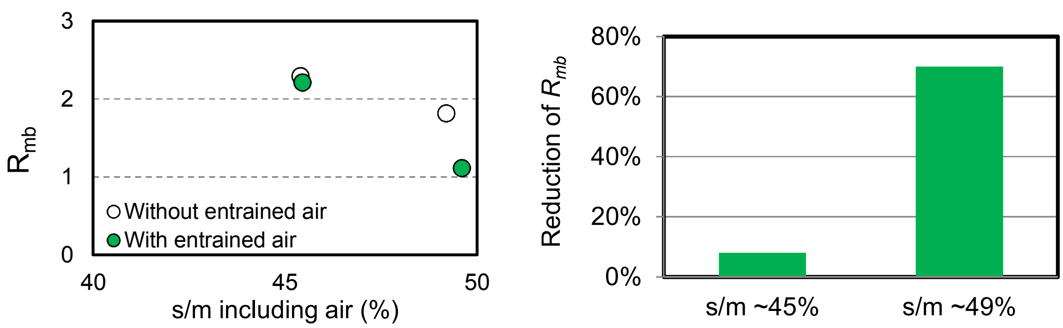
The degree of interaction between model coarse aggregate and mortar was calculated by $1\text{-}R_{mb}/R_m$ as mentioned in chapter 2 which indicated internal friction of mortar on flowability. High and low values mean high friction and low friction, repectively. This index is the relative funnel speed of mortar before and after adding glass beads (R_m and R_{mb}). $1\text{-}R_{mb}/R_m$ of mortar using conventional superplasticizer is shown in **Fig. 11 a)**. It can be seen that $1\text{-}R_{mb}/R_m$ slightly reduced due to entrained air in mortar with low s/m (s/m of approximately 45%). Negative result on flowability has been found in mortar with high s/m (s/m of approximately 49%). $1\text{-}R_{mb}/R_m$ increased from 0.41 to 0.46 due to entrained air because air bubbles could not enhance flowability by reducing internal friction in mortar. **Fig. 11 b)** shows the degree of mitigation of interaction between model coarse aggregate and mortar $\Delta(1\text{-}R_{mb}/R_m)$ which was the different value of $1\text{-}R_{mb}/R_m$ between mortar with entrained air and without entrained air as shown in equation (3).

$$\Delta(1-R_{mb}/R_m) = (1-R_{mb}/R_m)_{mortar\ with\ air} - (1-R_{mb}/R_m)_{mortar\ without\ air} \quad (3)$$



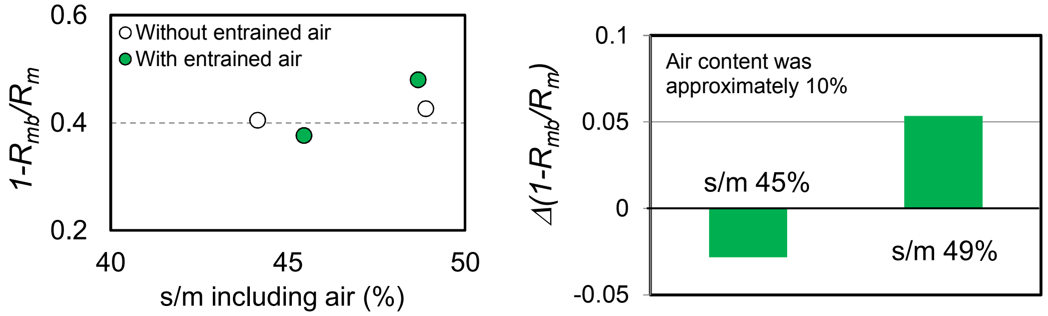
a) R_{mb} of mortar b) ΔR_{mb} due to entrained air

Fig. 9 Results of R_{mb} of mortar using conventional superplasticizer.



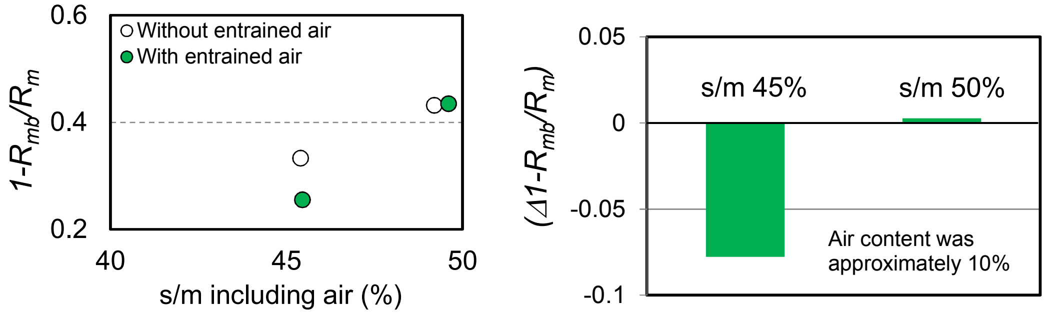
a) R_{mb} of mortar b) ΔR_{mb} due to entrained air

Fig. 10 Results of R_{mb} of mortar using new type of superplasticizer.



a) $1\text{-}R_{mb}/R_m$ of mortar b) $\Delta(1\text{-}R_{mb}/R_m)$ due to entrained air

Fig. 11 Degree of friction *($1\text{-}R_{mb}/R_m$)* of mortar using conventional superplasticizer.



a) $1\text{-}R_{mb}/R_m$ of mortar b) $\Delta(1\text{-}R_{mb}/R_m)$ due to entrained air

Fig. 12 Degree of friction *($1\text{-}R_{mb}/R_m$)* of mortar using new type of superplasticizer.

This index represents the reduction in internal friction of mortar by entrained air. In case of s/m of approximately 45%, the degree of mitigation of ($1\text{-}R_{mb}/R_m$) was observed. The degree of mitigation was approximately 0.03 which was small for increasing flowability of mortar. In case of s/m of approximately 49%, $\Delta(1\text{-}R_{mb}/R_m)$ was positive value because of the increase in friction. Degree of mitigation was approximately 0.05. This means that entrained air was not suitable for enhancing flowability in mortar with high fine aggregate content.

In case of mortar using new type of superplasticizer, the degree of interaction ($1\text{-}R_{mb}/R_m$) and degree of mitigation of interaction ($\Delta(1\text{-}R_{mb}/R_m)$) due to entrained air are shown in **Figs. 12 a)** and **12 b)**, respectively. It can be seen that $1\text{-}R_{mb}/R_m$ significantly reduced from 0.33 to 0.25 due to entrained air in mortar with low s/m (s/m of approximately 45%) because of effective ball bearing effect as shown in **Fig. 12 a)**. Negative result on flowability has been found again in mortar with high s/m (s/m of approximately 49%) which was similar to the result of mortar using conventional superplasticizer. $1\text{-}R_{mb}/R_m$ slightly increased according to the increase in internal friction. It can be concluded that ball bearing effect by entrained air could not reduce internal friction of mortar with high s/m resulting in worse flowability. **Fig. 12 b)** shows the degree of mitigation of interaction ($\Delta(1\text{-}R_{mb}/R_m)$) of mortar with new type of superplasticizer. In case of s/m of approximately 45%, $\Delta(1\text{-}R_{mb}/R_m)$ was 0.08, which was high. On the other hand, $\Delta(1\text{-}R_{mb}/R_m)$ of mortar with s/m of approximately 49% was positive with value of 0.003 which was very small.

Although entrained air could effectively increase the flowability of mortar by reducing internal friction, the problem of entrained air itself was air stability. It was observed that air content reduced approximately 50% in 30 minutes after mixing. At the 5th minutes, air content was approximately 9-10%, then it became approximately 7-8% before flowability test at the 20th minutes. Finally, air content reduced to approximately 5% at 30th minutes as shown in **Fig. 13**. Air content directly affected flowability and it also affected self-compactability of fresh concrete. Therefore, stability of entrained air has to be taken into account.

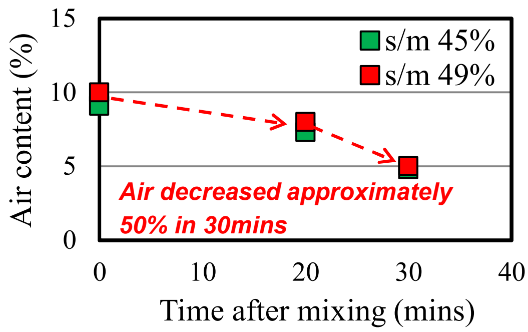


Fig. 13 High amount of air loss during 30 minutes.

4. Enhancement in flowability of mortar with an effective mixing procedure

The authors succeeded to increase flowability of mortar by employing entrained air with effective mixing method called “Water-dividing mixing method”. This mixing method was introduced based on the idea that quality of entrained air depends on condition of mortar portion before adding air entraining agent. The improvement of stability of entrained air and high quality of entrained bubbles on reduction rate of R_{mb} and mitigation of $(1-R_{mb}/R_m)$ were observed. In addition to the new mixing method, some mix proportions needed high amount of air entraining agent for producing target air content which was approximately 10%, and the difference in dosage of air entraining agent showed different results on flowability of mortar in spite of similar air content. Furthermore results of mortar experiment were verified with concrete experiment in order to confirm applicability for practical use. By using this mixing method, flowability and stability of entrained air were improved simultaneously. **Fig. 14** shows procedure of water-dividing method in details, it can be seen that half amount of total water with superplasticizer was added first and mixed for 60 seconds. At this point, mortar had wet condition. Finally, AE with another half amount of water was added and mixed for 60 seconds.

Significant result on reduction of R_{mb} was observed. The reduction of R_{mb} of mortar using new type of superplasticizer is shown in **Fig. 15**. Air content in mortar is in the range of 10-13%. High reduction of R_{mb} due to the presence of entrained air was observed in mortar mixed by simple mixing method which was approximately 60%. Low reduction of R_{mb} which was approximately 20% was observed in mortar mixed by water-dividing mixing method.

Although air content was approximately controlled in the range of 10-13%, dosages of AE were apparently different depended on mixing method. Effective bubbles for flowability enhancement could be produced by water-dividing mixing method with higher dosages of air entraining agent.

To achieve target air content of approximately 12-14%, dosage of air entraining agent was varied in accordance with mixing method. Small dosages of AE was sufficient for simple mixing method, whereas higher dosage was necessary for water-dividing mixing method as shown in **Fig. 16**. When high dosage of AE of 0.15% was added to mortar and mixed by simple mixing method, air content in the mortar was approximately 28% which was very high and it could not be applied for self-compacting concrete. Moreover, segregation of glass beads occurred due to excessive amount of air. In case of mortar mixed by water-dividing mixing method, target air content was achieved by adding dosage of AE of 0.05%. Saturated point of air content was observed at this point. Air content slightly increased from 12% to 14% by increasing dosage of AE from 0.05% to 0.20%. Although target air content could be achieved by wide range of AE dosage (0.05-0.20%), there might be effect of each AE dosage on flowability of mortar. Accordingly, degree of interaction between model coarse aggregate and mortar was examined.

Figure 17 shows the reduction of R_{mb} regarding to AE dosage and mixing method. Dosage of AE of over 0.05% was necessary for water-dividing mixing method, whereas it was only 0.005% for simple mixing method. Entrained air was not effective by simple mixing method. However, low reduction of R_{mb} was observed in mortar mixed by water-dividing mixing method with dosage of AE of over 0.15%.

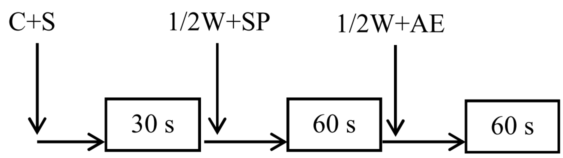


Fig.14 Water-dividing mixing method.

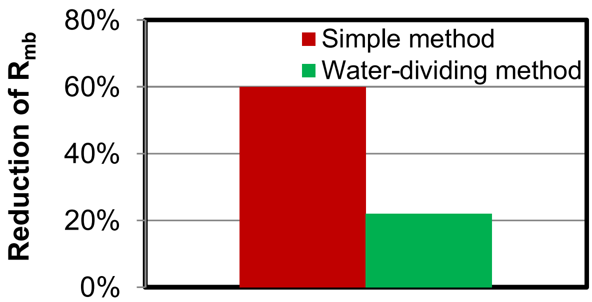


Fig. 15 Low reduction of R_{mb} due to the presence of entrained air with water-dividing mixing method in mortar using conventional superplasticizer.

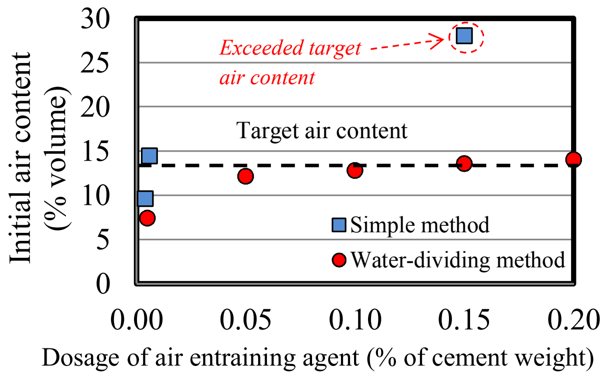


Fig. 16 Excessive dosage of AE was necessary to produce target air content for water-dividing mixing method.

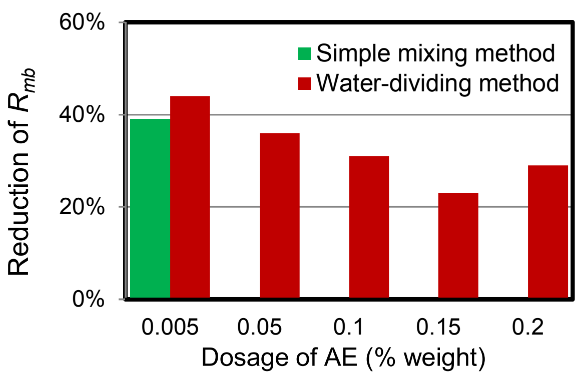


Fig. 17 Reduction of R_{mb} due to the increase in AE dosage in spite of similar air content.

The optimum dosage of AE was 0.15% that gave the lowest value of the reduction rate of R_{mb} as 22%. It became 29% by increasing dosage of AE to 0.20%. Despite the fact that dosage of AE of 0.05-0.20% could produce target air content, different result was apparently observed. The variation in dosage of AE might result in different characteristic of entrained bubbles for flowability and self-compactability enhancement of mortar and concrete. Although the reduction of R_{mb} was slightly over 20% by water-dividing mixing method, this values was the best among the other mortar mixes.

The interaction between model coarse aggregate and mortar ($1-R_{mb}/R_m$) was effectively reduced by entrained air produced by water-dividing mixing method as shown in **Fig. 18**. It almost reached 0.4 which was the desirable value for mortar that can be mixed with real coarse aggregate to be SCC. On the other hand, it apparently increased by simple mixing method in spite of slightly different air content. The preferable characteristic of entrained bubbles for flowability of mortar could be produced by water-dividing mixing method.

5. Air-enhanced self-compactability of fresh concrete

The effective mixing method was also verifed with concrete experiment. The method to test self-compactability of SCC referred to Recommendation for Self-Compacting Concrete issued by JSCE in 1999. The satisfied self-compacting concrete is concrete with filling height not less than 300 mm. The result was similar to that of mortar experiment that level of self-compactability of fresh concrete could be increased over 250 mm for obstacle level of R1 specified by JSCE due to entrained air of approximately 10% with water-dividing mixing method as shown in **Fig. 19**. The filling height of concrete could not reach more than 200 mm by the simple mixing method in spite of air content of approximately 15%. Photos of the self-compactabilty test of fresh concrete are shown in **Fig. 20**.

Figure 21 shows a comparison on the stability of entrained air in concrete between the simple mixing method and water-dividing method. It can be seen that reduction in air was only observed in concrete with simple method. On the contrary, air content slightly increased approximately 1% in concrete with the water-dividing method. This new type of mixing method could enhance self-compactability with entrained air and the stability of entrained air simultaneously.

By making use of an effective mixing method for entrained air, the mix proportion of air-SCC with high level of self-compactability can be created. The ratio of fine aggregate in mortar (s/m) and water to cement ratio (W/C) could be increased to 55% and 45%, respectively by entraining 10% of entrained air as shown in **Fig. 22**. Specific gravity of conventional SCC and air-SCC were approximately 2.39 and 2.16, respectively. This resulted

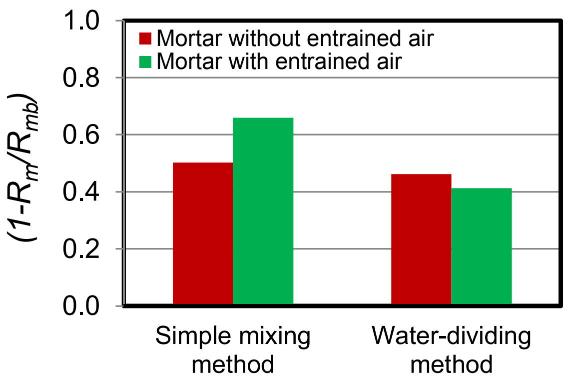


Fig. 18 Mitigation in ($1-R_{mb}/R_m$) due to water-dividing mixing method.

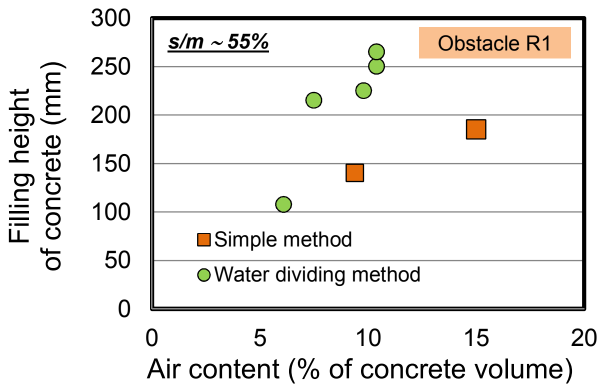
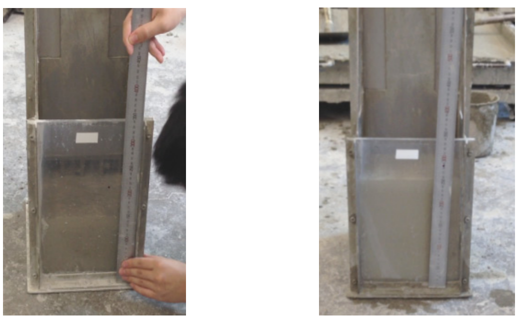


Fig. 19 High level of self-compactability with air bubbles entrained by water-dividing mixing method.



a) Simple method b) Water-dividing method

Fig. 20 Self-compactability test of fresh concrete.

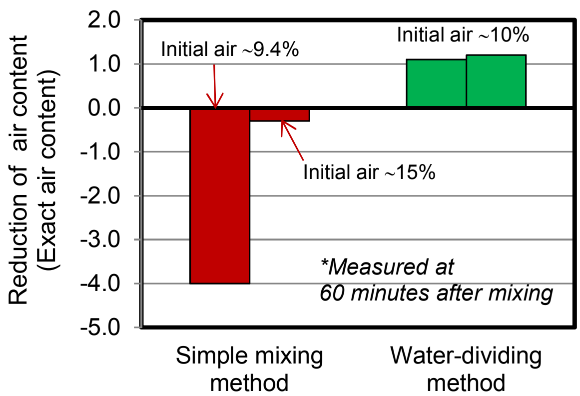


Fig. 21 Reduction of air content 60 mins after mixing.

Table 2 Mix proportions of conventional SCC and air-SCC.

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

in a significant reduction in unit cement content in mix proportion. Accordingly, a new type of self-compacting concrete with lower unit cement content by entraining air of 10% of concrete volume called "Air-enhanced Self-Compacting Concrete (air-SCC) has been succeeded. The volume fractions of materials in the ordinary concrete, SCC and air-SCC are shown in **Fig. 23**.

The unit mass of each material in conventional SCC with air content of 4% and air-SCC with air content of 10% are shown in **Table 2**. Conventional SCC needs cement content approximately of 600 kg/m^3. Cement content in air-SCC is approximately 370 kg/m^3, which is lower than that of the conventional SCC owing to the increase in s/m in the mix.

One of the most important properties of concrete is compressive strength. Strength of concrete gradually decreased due to the increase in air content because of the loss of density itself. **Figure 24** shows the reduction in compressive strength due to the increase in air content of air-SCC. The target air content of air-SCC is 10%. It can be seen that compressive strength is approximately 40N/mm^2 with air content of approximately 10%. Compressive strength of air-SCC is higher than compressive strength of normal concrete which is approximately 30N/mm^2. Accordingly, it can be said that air-SCC is capable to be used for general reinforced concrete structures with moderate compressive strength.

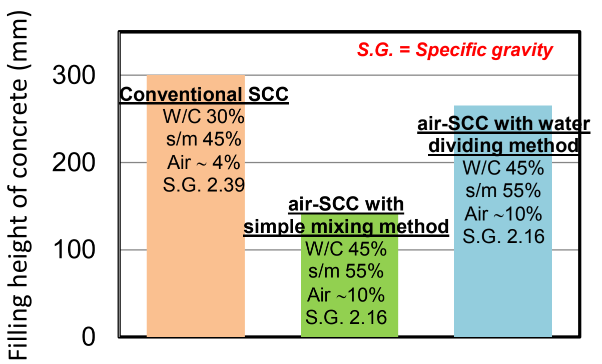


Fig. 22 Mix proportion of air-SCC with high level of self-compactability.

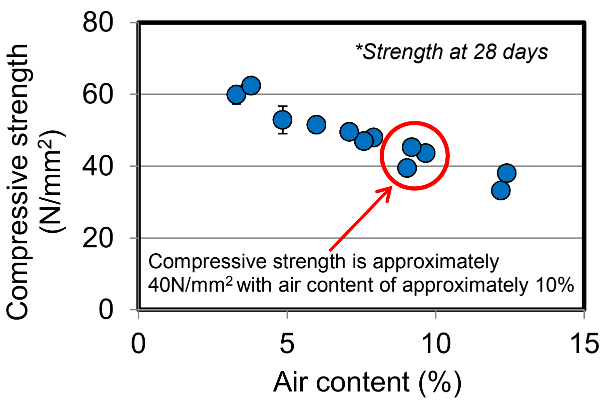


Fig. 24 Compressive strength of air-SCC with different air contents.

6. Finer air for higher level of self-compactability

This section presents the characteristic of entrained bubbles in mortar and concrete specimens at hardened state and its effect on fresh properties of mortar and concrete. To measure characteristic of entrained bubbles in specimens, Linear Traverse Method (LTM) was performed in accordance with ASTM C457-08 (ASTM 2008) which is one-dimensional analysis, as shown in **Fig. 25**.

Specimens were prepared according to standard size which was 100mm in diameter and 200mm in height for mortar specimens and 150mm in diameter and 300mm in height for concrete specimens. The depth of specimens prepared for LTM was 50 mm. which was cut from cylinder specimens with 100mm and 150mm in diameter for mortar and concrete specimens, respec-

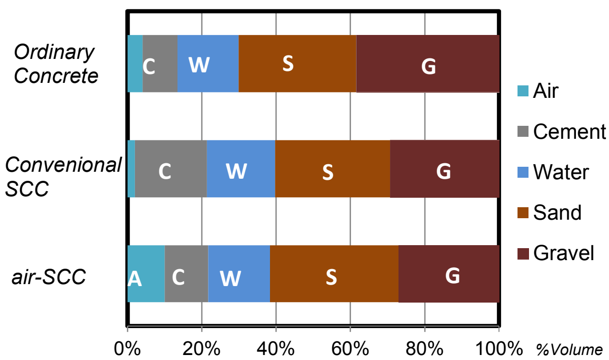


Fig. 23 Volume fraction of materials in concrete.

Fig. 25 Linear Traverse Machine.

Table 3 Details of mortar specimens for LTM.

Mixing method	*W/C*	*s/m*	SP	AE dosage (% of cement)
Simple method	45%	57%	SP1	0.006
			SP2	0.006
Water-dividing method			SP1	0.010
			SP2	0.005
				0.050
				0.100
				0.150
				0.200

tively. In order to measure bubbles diameter on average, specimens were cut into 3 pieces representing characteristic of bubbles in top zone, middle zone and bottom zone of specimens. Cutting method of specimens is shown in **Fig. 26**.

Air bubbles were measured on both sides of each piece of specimens. It means that 6 planes were measured for each specimen. Air content, diameter size of bubbles, number of bubbles and specific surface area were automatically calculated in accordance with ASTM C457 (ASTM 2008) by computer program which has been installed and connected to the measuring machine.

6.1 Bubble size distribution in mortar specimens

Characteristic of entrained bubbles in mortar specimens mixed by simple and water-dividing mixing method with conventional superplasticizer (SP1) and new-type superplasticizer (SP2) were measured. Dosage of AE was varied because sufficient dosage for achieving target air content was different. Target air content in mortar was approximately 10%. Details of mortar specimens brought to be measured for their characteristic of bubbles are listed in **Table 3**.

In this study, capillary pore was not considered because of its very small size (smaller than 5μm). It could not be observed by visual observation. Moreover, the smallest size which can be detected by this measuring method is 10μm. Accordingly, air bubbles counted by this machine were entrained air and entrapped air. Diameter size obtained from LTM was average values in each group of bubbles size. For example, air content of bubbles with diameter in range of 10-50μm will be shown as the average diameter size of 25μm. The largest air bubbles were bubbles with 2.5mm in average diameter. This size of air bubble was observed only in mortar with normal dosage of AE.

Mixing method and dosage of air entraining agent significantly affected the production process of entrained air. In spite of similar air content, diameter size of air bubbles produced by simple and water-dividing method was apparently different. Bubble size distributions of entrained air in mortar specimens using SP1 and SP2 are shown in **Fig. 27**.

In case of mortar using SP1, air contents at hardened state of mortar mixed by simple and water-dividing method were 13.0% and 8.6% respectively. It can be seen that water-dividing mixing method produced large amount of small bubbles, whereas large bubbles were slightly produced. On the other hand, large amount of large bubbles were produced by simple mixing method. Although air content of specimen mixed by water-dividing mixing method was 8.6% which was lower than that of specimen mixed by simple mixing method which was 13%, volume of small air bubbles was close to each other. The difference in air volume mainly depended on air volume in zone of large bubbles size.

In case of mortar using SP2, air content produced by simple mixing method and water-dividing mixing method were slightly different which were 12% and 13.4% respectively. Despite the fact that air contents were slightly different, bubble size distributions were obviously different. Tendency of the distribution was similar to that of specimens with conventional superplasticizer (SP1) that high volume of small air bubbles

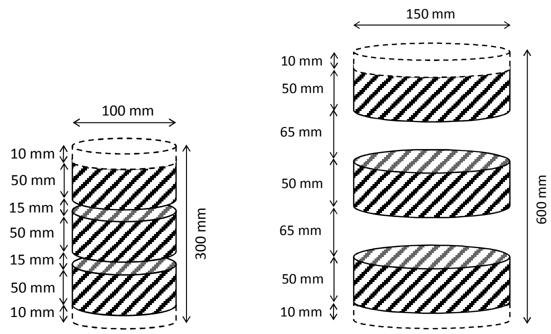


Fig. 26 Specimens prepared for LTM.

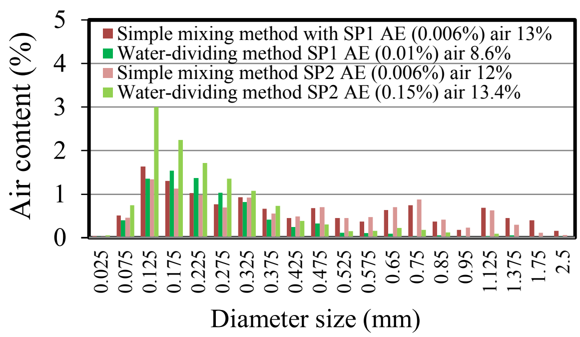


Fig. 27 Bubble size distributions of entrained air in mortar specimens with SP1 and SP2.

appeared in mortar with water-dividing mixing method. And high volume of large air bubbles was observed in mortar with simple mixing method. The difference in bubbles size distribution of entrained air related to the reduction in degree of friction in mortar ($1-R_{mb}/R_m$). The effective reduction in degree of ($1-R_{mb}/R_m$) might be due to high amount of small air bubbles that could be seen apparently in case of mortar mixed by water-dividing mixing method with SP2 and excessive dosage of AE (AE 0.15%).

Large amount of small air bubbles was produced by water-dividing mixing method in which air entraining agent was added at the last step. Small bubbles could be greatly produced in mortar with low friction condition by mixing half of water with superplasticizer before adding air entraining agent. However, high dosage of air entraining agent was necessary to produce target air content for new mixing method because of its low inside friction especially for mortar using new-type superplasticizer. There might be some part of air bubbles destroyed by viscosity agent blended in new-type superplasticizer.

Furthermore, effect of excessive dosage of air entraining agent with water-dividing mixing method on bubbles size distribution mortar was also studied because there was significant mitigation in ($1-R_{mb}/R_m$) by adding various excessive dosage of AE. **Figure 28** shows bubble size distributions of mortars mixed by water-dividing mixing method with variation of excessive dosage of air entraining agent. The tendencies of size distribution of mortar with excessive dosage of AE were almost similar, except mortar with AE dosage of 0.2%. Although AE dosage was added at 0.2% but volume of small bubbles was obviously lower than that of mixes added with AE dosages of 0.05%, 0.10% and 0.15%. Moreover, volume of large bubbles was higher than that of the other mixes. It was higher than that of mortar with AE dosage of 0.15%, although total air content was lower. This might be the results of adding overdosage of air entraining agent to the mix so that the applied energy of new mixing method was not sufficient for this dosage. It can be said that the optimum dosage of air entraining agent was 0.15% of cement weight in term of mitigation in ($1-R_{mb}/R_m$).

Air content of mortar with AE dosage of 0.005% was only 4.5% which was very low comparing to mortar with the dosage of AE of 0.006% with simple mixing method. This was also caused by soft condition of mortar before adding air entraining agent. Air content of over 10% was difficult to produce in mortar with high flowability. Therefore excessive dosage of AE was necessary for achieving target air content which was in range of 10-13%. To achieve target air content, AE dosage over 0.05% was necessary. Although air content increased up to 13.4% by adding AE of 0.15%, it dropped to 11.2% by adding AE of 0.20%. In fact, initial air content of mortar with an added AE dosage of 0.20% was 14% which was higher than that of the mix with an added AE of 0.15% which was 13.6%, however air loss during hardening was higher. High amount of air loss depended on high amount of large bubbles (larger than 0.3 mm) which is easy to escape in mortar with AE dosage of 0.20%.

The example photos of air bubbles in mortar at hardened state measured by LTM are shown in **Fig. 29**. It can be seen that large bubbles were obviously observed in mortar specimens mixed by simple mixing method as shown in **Figs. 29 a)** and **b)**. On the contrary, large bubbles were slightly observed in mortar specimens mixed by water-dividing mixing method as shown in **Figs. 29 c)** and **d)**.

The mechanism of flowability and self-compactability enhancement by entrained air was explained by ball bearing effect. The image of the presence of large bubbles in mortar is shown in **Fig. 30 a)**. It can be seen that there are large gap between air bubbles inside mortar matrix. Comparing number of bubbles with the same air volume, once diameter of air bubbles become half of large bubbles, number of bubbles becomes 8 times according to equation (3). Moreover, total surface area of

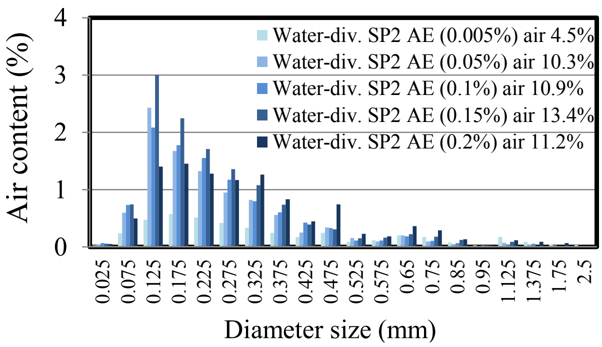
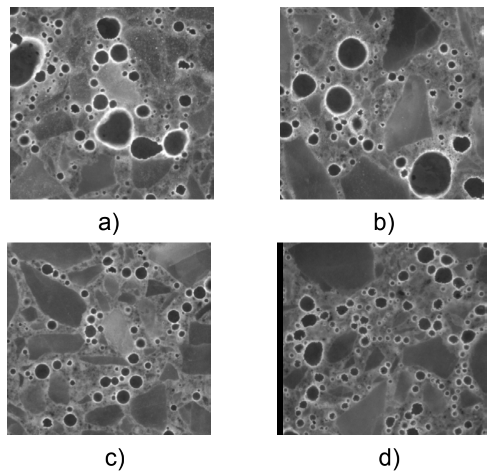


Fig. 28 Bubble size distributions of mortar using SP2 mixed by water-dividing mixing method.



a) Simple mixing method with SP1 and AE 0.006%
b) Simple mixing method with SP2 and AE 0.006%
c) Water-dividing method with SP1 and AE 0.01%
d) Water-dividing method with SP2 and AE 0.15%

Fig. 29 Example photos of air bubbles in mortar specimens.

bubbles will be higher which is one of the important factors on flowability and self-compactability enhancement. The image of distribution of small air bubbles in mortar is shown in **Fig. 30 b)**. High amount of bubbles appeared among sand particles and model coarse aggregate. Furthermore touching points between air bubbles and solid particles were high due to large amount of bubbles which resulted in effective enhancement of flowability of mortar.

$$V_{sphere} = \frac{4}{3}\pi r^3 \tag{3}$$

where V_{sphere}: Volume of air bubbles and r: Radius of bubbles.

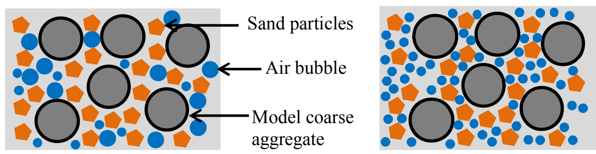
Additionally, the behavior of small and large air bubbles during deformation was assumed that they behaved differently due to the difference of characteristic of bubbles itself. By assuming that thickness of surface of large and small bubbles was similar, thus the aspect ratio (thickness/diameter) of small bubbles was higher than that of large bubbles. It meant that small bubbles were more capable to resist or absorb the compression forces due to the approaching of model coarse aggregate during deformation. **Figure 31** shows the behavior of small and large bubble when it was compressed by coarse aggregate. Shape of large bubbles considerably changed attributed to compression forces because of low aspect ratio. Therefore, bubbles tried to move away from the original position resulting in the collision of aggregate and produced friction in mortar matrix. Conversely, small bubbles with high aspect ratio effectively resisted these compression forces during deformation. It slightly deformed due to the approaching of coarse aggregate, thus bubbles with high aspect ratio could resist compression forces and also interacted with aggregate by introducing rebounding force. This behavior was a part of ball bearing effect which enhanced flowability and self-compactability of fresh concrete.

6.2 Bubbles size distribution in concrete specimens

Bubble size distribution of entrained air in concrete specimens also depended on mixing method and dosage of AE added to the mixes. **Figure 32** shows bubble size distribution by simple and water-dividing mixing method. In case of concrete with AE dosage of 0.005%, it can be seen that volume of small air bubbles of concrete mixed by simple mixing method was slightly higher than that of concrete mixed by water-dividing mixing method in spite of lower total air content. This resulted in higher filling height of box test. Filling height of concrete mixed by simple and water-dividing mixing method was 140 mm and 108 mm respectively. Despite the fact that air content of concrete mixed by water-dividing mixing method was higher which was 5.4% but volume of effective bubbles on self-compactability enhancement was slightly lower. Therefore filling height of concrete mixed by simple mixing method was higher than that of concrete mixed by water-dividing mixing method. However filling height could not reach 250 mm and air content was lower than 10% which was the target air content, thus excessive dosage of AE was added and mixed by both mixing methods.

In case of concrete with AE dosage of 0.15%, bubble size distribution was similar to that of mortar specimens in such a way that large bubbles were slightly produced. Air volume in zone of small bubbles of specimen mixed by water-dividing mixing method was higher than that of specimen mixed by simple mixing method, resulted in higher values of filling height of concrete box test which were 250 mm and 185 mm. It can be said that self-compactability of fresh concrete could be improved by water-dividing mixing method with excessive dosage of AE. Eventually, the desirable filling height of SCC was achieved by this combination.

The comparison of bubble size distributions of specimens mixed by water-dividing mixing method with various dosages of AE is shown in **Fig. 33**. Dosages of air entraining agent were varied at 0.005%, 0.05%, 0.10% and 0.15%. Bubble size distribution tended to be similar. Volume of bubbles with diameter size larger than 0.5mm was rarely observed, except specimen with



a) Large air bubbles **b)** Small air bubbles

Fig. 30 Number of bubbles in mortar with different size, considered the same air content.

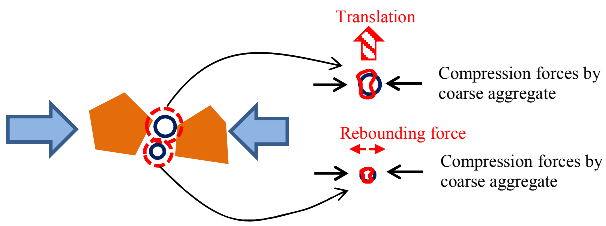


Fig. 31 Small and large bubble under compression forces by coarse aggregate.

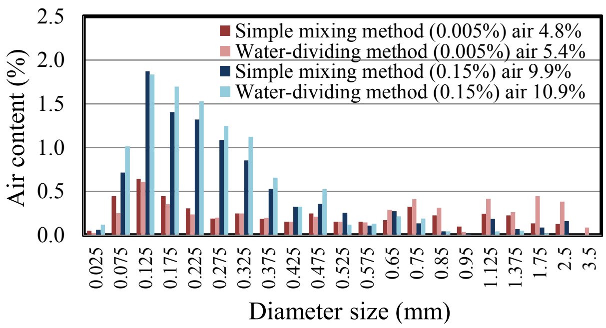


Fig. 32 Bubble size distributions of entrained air in concrete.

AE dosage of 0.005%. High amount of large bubbles was found by adding normal dosage of AE. Although air content of concrete with AE dosage of 0.005% was the lowest, volume of large bubbles was the highest among this group of specimens. In concrete with excessive dosage of AE (AE dosage over 0.05%), volume of all size of bubbles tended to be levelly increased due to the increase in air content. At this point, self-compacting concrete with air content of approximately 11% and sufficient self-compactability which was over 250mm. was achieved. This type of concrete is named as Air-enhanced self-compacting concrete (air-SCC).

6.3 Total surface area of entrained bubbles in mortar specimens

According to the different diameter size of entrained bubbles due to different mixing method considering similar amount of air content, total surface area of bubbles was calculated because total surface area was obviously varied due to the change of diameter size. It was clear that small bubbles were suitable for flowability improvement, thus total surface area was the main factor on flowability and self-compactability. In this section, total surface area was calculated and clarified its relationship with flowability of mortar and level of self-compactability of concrete.

Figure 34 shows the total surface area of entrained bubbles which was separately considered in each size. These values were calculated from entrained air volume obtained from LTM. It can be seen apparently that the effective bubbles that contribute to total surface area were small bubbles especially bubbles with diameter smaller than 0.3mm. The highest total surface area was approximately 415mm^2/100mm^3 by water-dividing method with AE dosage of 0.15%, whereas, it was approximately 263mm^2/100mm^3 by simple mixing method with AE dosage of 0.006%.

Although total surface area of bubbles in mortar with water-dividing method and SP2 was higher than that of mortar with simple mixing method, air content was 8.1% which was lower than 11.5% in mortar with simple mixing method. Proportion of surface of bubbles with diameter smaller than 0.3mm was approximately 75% in mortar with simple mixing method and 90% in mortar with water-dividing method as shown in **Fig. 35**.

In spite of similar air content in mortar, total surface area of entrained bubbles was different due to the characteristic of bubbles itself. **Figure 36** shows relationship between air volume and total surface area of bubbles in mortar with different mixing methods. In mortar mixed by water-dividing method, total surface area of bubbles gradually increased due to the increase in air volume.

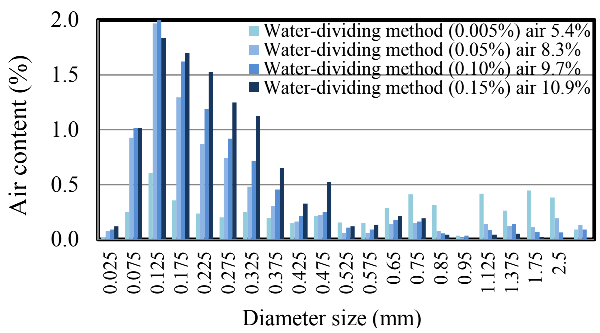


Fig. 33 Bubble size distributions of entrained air by water-dividing mixing method.

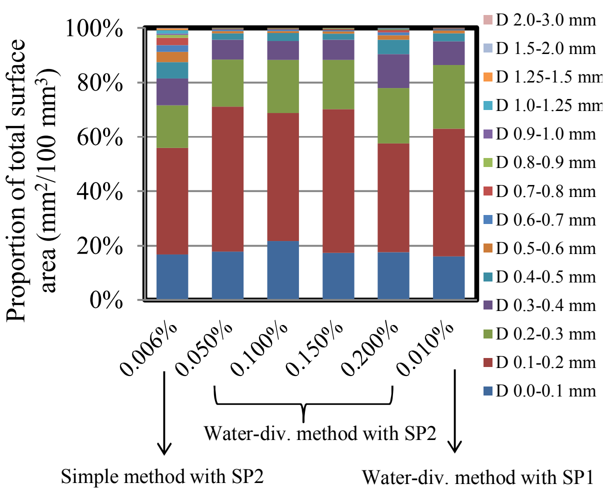


Fig. 35 Proportion of total surface area of bubbles in mortar.

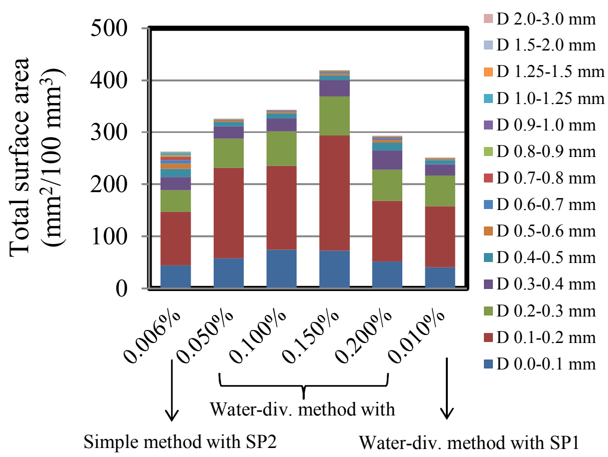


Fig. 34 Proportion of surface area of bubbles of each diameter size.

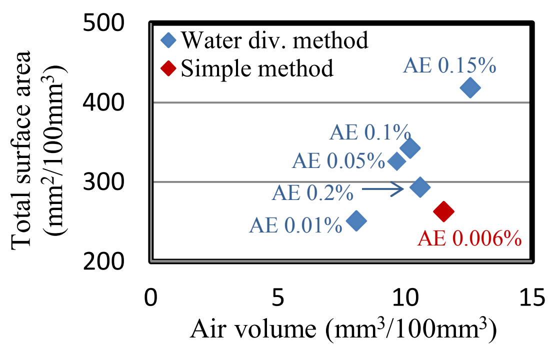


Fig. 36 High total surface area of bubbles due to water-dividing method.

This relationship was almost linear because the proportion of each size of bubbles was almost similar. Total surface area of bubbles in mortar mixed by simple mixing method was apparently different from that in mortar mixed by water-dividing method. It can be seen that total surface area was approximately 263mm^2/100mm^3 with air volume of approximately 11.5mm^3/100mm^3 in mortar mixed by simple mixing method whereas it was approximately 343mm^2/100mm^3 with air volume of approximately 10.6mm^3/100mm^{3}in mortar mixed by water-dividing method.

Despite the fact that air volume in mortar mixed by water-dividing method was lower, total surface area was higher because of high volume of small bubbles which was main influence on total surface area. Accordingly, total surface area of bubbles was considered as the main parameter affecting the degree of interaction between model coarse aggregate and mortar *(1-R_{mb}/R_m)*.

The amount of small entrained bubble was an influence factor on the reduction in funnel speed of mortar with glass beads (R_{mb}) due to the presence of entrained air which significantly related to total surface area of bubbles. **Figure 37** shows relationship between total surface area of bubbles and the reduction of R_{mb} due to the presence of entrained air. It can be seen that the reduction of R_{mb} gradually reduced due to the increase in total surface area of bubbles. It was lowest at approximately 23% in mortar with total surface area of bubbles approximately 415mm^2/100mm^3. This means that the funnel speed of mortar with glass beads (R_{mb}) slightly reduced due to the increase in number of touching point between air bubbles and glass beads resulting in preferable movement of glass beads in mortar. On the contrary, it was highest at approximately 40% according to total surface area of bubbles approximately 260mm^2/100mm^3. In this case, the reduction of R_{mb} was high which meant that the movement of glass beads was not apparently enhanced by small number of touching point between air bubbles and glass beads.

Figure 38 shows the degree of *(1-R_{mb}/R_m)* regarding to total surface area of entrained bubbles. *(1-R_{mb}/R_m)* gradually reduced according to the increase in total surface area. *(1-R_{mb}/R_m)* almost reached the desirable value of self-compacting mortar which was 0.4 with total surface of approximately 418 mm^2/100mm^3. To achieve high total surface area of bubbles, water-dividing method with excessive dosage of AE was necessary. The optimum AE dosage was 0.15%, however, total surface area reduced to approximately 293 mm^2/100mm^3 by adding AE dosage of 0.20%. Total surface area could not be made over 300 mm^2/100mm^3 by simple method. It was approximately 263 mm^2/100mm^3 with air content of 11.5 mm^3/100mm^3 in this study.

It can be seen that the relationship between total surface area of bubbles and *(1-R_{mb}/R_m)* seem to have linear relation. However, point of mortar with AE dosage of 0.2% was out of the trend. It might be due to the error in measuring procedure. Accordingly, air content at hardened state was measured by weight and compared with air content measured by LTM. **Fig. 39** shows the error of measuring air content by LTM. The difference of air content measured by weight and LTM of mortar with AE dosage of 0.00%, 0.05%, 0.10% and 0.015% were small which were lower than 1.0%. Air content of mortar with AE dosage of 0.20% measured by LTM apparently differed from that by weight by approximately 2.5%. Undetectable bubbles might exist in this case. This error resulted in low total surface area of mortar with AE dosage of 0.20% that made data out of linear relation in **Figs. 40** and **41**.

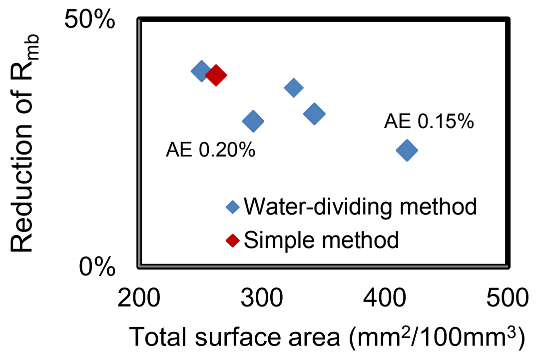


Fig. 37 Reduction of R_{mb} with the increase of total surface area of bubbles.

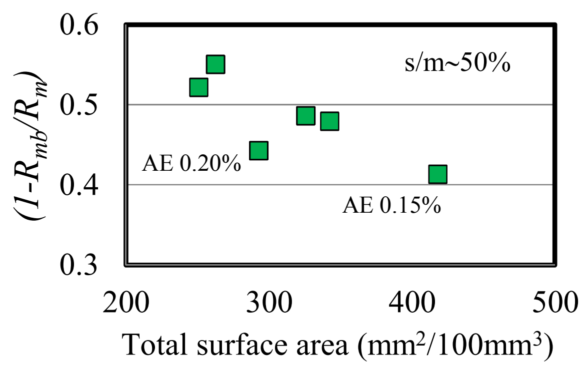


Fig. 38 Degree of (*1-R_{mb}/R_m*) due to total surface area of bubbles.

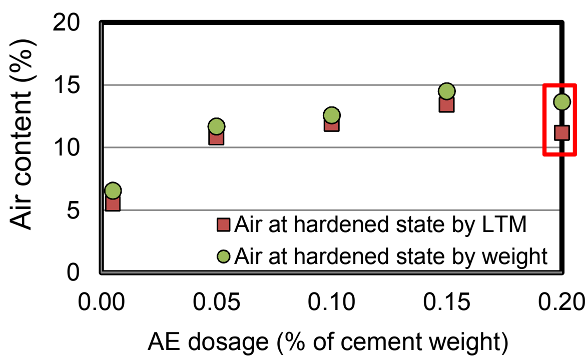


Fig. 39 A significant difference of air content of mortar measured by weight and LTM with AE dosage of 0.2%.

6.4 Total surface area of entrained bubbles in concrete specimens

Total surface area of entrained bubbles in concrete depended on mixing method as well and was similar to the results of mortar. **Figure 40** shows the total surface area in each size of bubbles. Total surface area of bubbles in concrete with normal AE dosage (0.005%) was small because of low air contents, which were 4.8% and 5.4% by simple and water-dividing mixing method, respectively, and high volume of large bubbles. By using excessive dosage of AE with simple mixing method, air content was 9.9% with total surface area of 312.8 $mm^2/100mm^3$. Total surface area gradually increased from 298.4 to 374.0 $mm^2/100mm^3$ due to the increase in air content from 7.9 to 10.9% by increasing AE dosage from 0.05 to 0.15% in concrete with water-dividing mixing method.

Volume of small bubbles significantly influenced the total surface area especially diameter smaller than 0.3mm as shown in **Fig. 41**. The proportion of surface of bubbles with diameter smaller than 0.3mm was approximately 70-80% by using normal AE dosage. It was approximately 85-90% in concrete with excessive dosage of AE mixed by both mixing methods.

With similar air volume of approximately 10%, high total surface area could be produced by water-dividing mixing method comparing to total surface area in concrete with simple mixing method as shown in **Fig. 42**. Consider similar air volume at approximately 10%, total surface area in concrete with water-dividing mixing method was 374 $mm^2/100mm^3$, and it was 312.8 $mm^2/100mm^3$ in concrete with simple mixing method. This resulted in higher level of self-compactability by water-dividing mixing method.

Total surface area significantly related to self-compactability of fresh concrete as shown in **Fig. 43**. Filling height of concrete gradually increased due to the increase in total surface area of bubbles. Level of self-compactability with filling height of 250mm was achieved in concrete with total surface area of approximately 374 $mm^2/100mm^3$ which could be produced by water-dividing mixing method with excessive dosage of AE.

7. Conclusions

Based on experimental results and analysis, conclusions can be written as follows:

(1) A simple mixing method in which all the materials were poured at once could not entrain suitable bubbles for enhancement in self-compactability of SCC.

(2) A New mixing method called "water-dividing

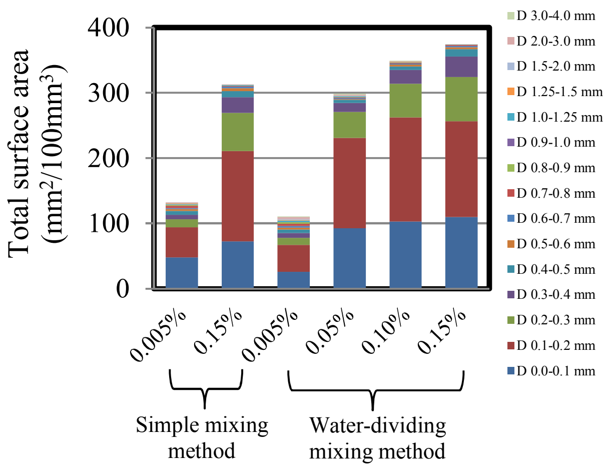


Fig. 40 Total surface area of bubbles of each diameter size in concrete.

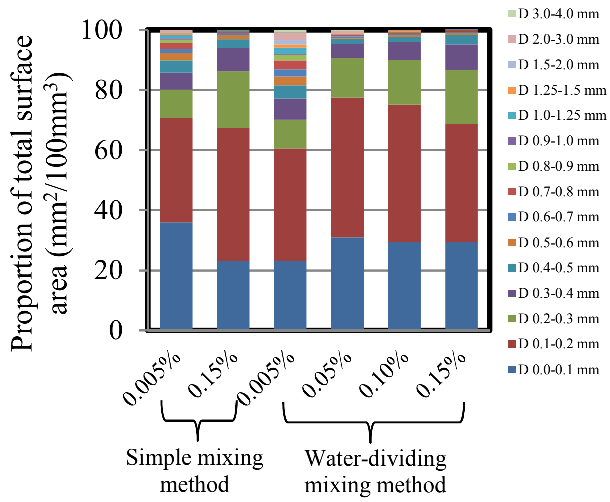


Fig. 41 Proportion of total surface area of bubbles in concrete.

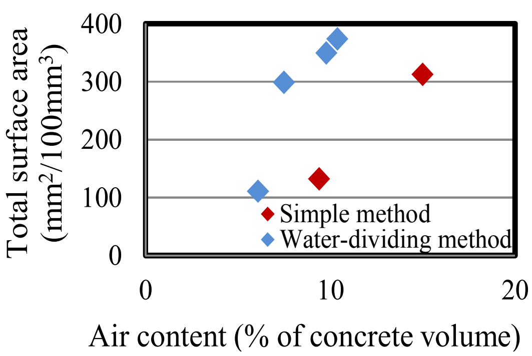


Fig. 42 Total surface area of bubbles in concrete.

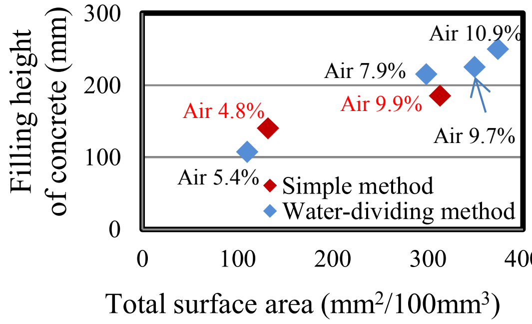


Fig. 43 Filling height increases with the increase of total

method" with excessive dosage of air entraining agent (AE) entrained high amount of small air bubbles which was suitable for reduction in friction in mortar during deformation.

(3) The larger total surface area of entrained air bubbles due to high amount of small air bubbles resulted in the higher level of reduction in friction of fresh mortar due to the existence of model coarse aggregate, resulting in higher level of self-compactability of fresh concrete.

(4) The authors succeeded in developing self-compacting concrete (SCC) with lower cement content with the air content of approximately 10%. This concrete was named as "air-enhanced self-compacting concrete (air-SCC).

Acknowledgement

All experiments in this research were instructed by Mr. Hideo Miyazi, technical instructor at department of infrastructure system engineering, Kochi University of Technology. Moreover, LTM measurement was performed at BASF Japan.

References

ASTM C457-08, (2008). "*Standard test method for microscopical determination of parameters of the air-void system in hardened concrete*." American Society for Testing and Materials, USA.

Attachaiyawuth, A. and Ouchi, M., (2013). "Factors influence the mitigation of the interaction between coarse aggregate and mortar in self-compacting concrete." *Internet Journal of Society for Social Management Systems*, 3. SMS13-1175

Attachaiyawuth, A., and Ouchi, M., (2014). "Effect of entrained air on mitigation of reduction in interaction between coarse aggregate and mortar during deformation of self-compacting concrete at fresh state." *Proceeding of the Japan Concrete Institute, JCI ,* 36(1), 1444-1449.

Attachaiyawuth, A., Tanaka, K., Rath, S. and Ouchi., M., (2015). "Air-enhanced self-compactability of fresh concrete with effective mixing method." *Proceeding of the Japan Concrete Institute, JCI ,* 37, 1069-1074.

JSCE, (1998). "*Recommendation for Self-Compacting Concrete*." Japan Society of Civil Engineers, Japan.

Okamura, H., Maekawa, K. and Ozawa, K., (1993). "*High Performance Concrete*." Gihodo Publishing. (in Japanese)

Okamura, H. and Ozawa, K., (1995). "Mix-design of self-compacting concrete." *Concrete Library of JSCE*, 25, 107-120.

Okamura, H. and Ouchi, M., (2003). "Self-compacting concrete." *Journal of Advanced Concrete Technology*, 1(1), 5-15.