- Technical Paper -

EFFECT OF ENTRAINED AIR ON MITIGATION OF REDUCTION IN INTERACTION BETWEEN COARSE AGGREGATE AND MORTAR DURING DEFORMATION OF SELF-COMPACTING CONCRETE AT FRESH STAGE

Anuwat ATTACHAIYAWUTH[*1] and Masahiro OUCHI [*2]

ABSTRACT

Effect of entrained air on mitigation of interaction between coarse aggregate and mortar during deformation of self-compacting concrete at fresh stage was investigated. The mitigation in interaction between coarse aggregate and mortar by entrained air was classified into 2 types, which were effect of volumetric increase in paste and ball bearing effect. The index for interaction between coarse aggregate and mortar was the reduction rate in the funnel speed of mortar due to model coarse aggregate. Ball bearing effect was observed in mortar using only two types of air entraining agent and ball bearing effect depended on type of air entraining agent and fine aggregate content.

Keywords: self-compacting concrete, entrained air, interaction between coarse aggregate and mortar, fine aggregate content in mortar, ball bearing effect, air entraining agent.

1. INTRODUCTION

Entrained air is added to concrete mix in order to improve freezing and thawing resistance of concrete in cold environment. Furthermore, slump of fresh concrete can be increased approximately 10 to 50 mm by increasing entrained air approximately 5% [1]. There are no researches considering the effect of entrained air on flowability of SCC have been clarified quantitatively.

The authors have set up 2 mechanisms of effect of entrained air on reduction in interaction between coarse aggregate and mortar: (1) Volumetric increase in paste and (2) Ball bearing effect. Volumetric increase of mortar by entrained air, total volume of mortar increased due to the increase in entrained air. Therefore, sand to mortar ratio (s/m) reduced consequently, resulted in the reduction in the degree of interaction between coarse aggregate and mortar. 2. Ball bearing effect, the presence of entrained air enhanced flowability of SCC by trundling sand particles inside concrete matrix, thus fine aggregate content in mix can be increased. However, entrained air bubbles have to be strong enough to maintain characteristic of bubbles against the deformation of concrete matrix during concrete flowing, otherwise bubbles may be broken, result in less efficiency on reduction in interaction between coarse aggregate and mortar. Therefore the aim of this study is to clarify effects of entrained air on the degree of interaction between coarse aggregate and mortar of self compacting concrete.

2. TESTING METHOD FOR DEGREE OF INTERACTION BETWEEN COARSE AGGREGATE AND MORTAR ($1-R_{mb}/R_m$)

The degree of interaction between coarse aggregate and mortar ($1-R_{mb}/R_m$) is an index, which indicates the shear deformation resistance of mortar when the normal stress approached by coarse aggregate, as shown in Fig. 1 [2]. R_m and R_{mb} indicate the flowability of mortar and mortar with model coarse aggregate respectively, which can be obtained from the mortar funnel test, as shown in Fig. 2 [3]. R_m and R_{mb} are defined as equation (1) and (2) respectively [4]. The $1-R_{mb}/R_m$ depends on characteristic of solid particles inside concrete matrix, hence this index will be increased due to the increase in fine aggregate content (s/m). Accordingly, to increase s/m and maintain proper value of $1-R_{mb}/R_m$ simultaneously was considered in this study.

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

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

where,

t_m : funnel time of mortar (sec)

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

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*1 Ph.D. student, Dept. of Infrastructure Systems Engineering, Kochi University of Technology, JCI Student Member

*2 Prof., Dept. of Infrastructure Systems Engineering, Kochi University of Technology, JCI Member

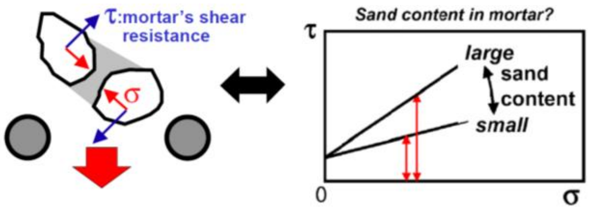


Fig.1 Shear resistance of mortar (τ) in accordance with normal stress (σ)

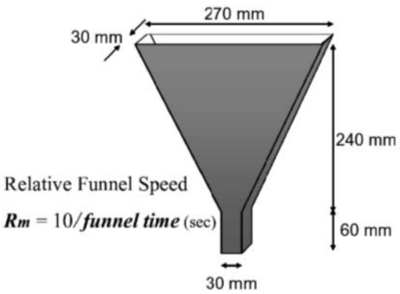


Fig. 2 Mortar funnel test [3]

Fig. 3 shows relationship between flowability of mortar R_m and mortar with model coarse aggregate R_{mb}. Flowability of mortar was reduced due to the presence of model coarse aggregate. Degree of reduction in flowability of mortar by the presence of model aggregate depend on varouis factors such as W/C, s/m, type of air entraining agent etc.

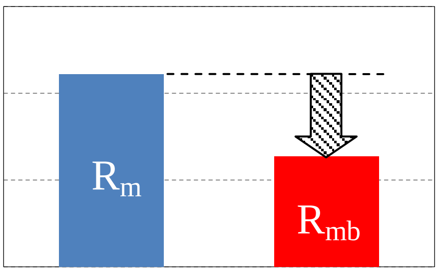


Fig. 3 Flowability of mortar (R_m) and mortar with model coarse aggregate (R_{mb})

2.1 Materials used

Table 1 shows the materials used in this study, which is produced in Japan. Conventional type and new type of superplasticizer called SP1 and SP2 respectively were employed in this study. SP1 was developed more than 10 years ago and SP2 was developed in order to increase W/C in mix by adding viscosity agent during production process. Therefore, SP2 contain viscosity agent, conversely no viscosity agent in SP1. 3 types of air entraining agent which are different in substrate were used in order to compare the effect of ball bearing effect in SCC. To avoid laborious work by mixing concrete with coarse aggregate, glass bead was applied as model coarse aggregate represented coarse aggregate to mortar experiments [4]. Model coarse aggregate has 10 mm. diameter and density is approximately 2.55 g/cm^3, which is almost the same as coarse aggregate.

Table 1 materials used

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/cm3, 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 1	Alkyl ether-based anionic surfactants
AE 2	Modified rosin acid compound-based anionic surfactants
AE 3	High-alkyl carboxylic acid-based anionic surfactants and non-ionic surfactant

2.2 Mix proportions

Mix proportions are shown in Table. 2. Original s/m was varied because target s/m including volume of air were approximately 45%, 50% and 53%. Volume of air was produced approximately in range 7-12%.

Table 2 Mix proportions

Parameter	Value
Original s/m	Varied from 50%-56% by volume, depend on target s/m
W/C	45% by weight
Model coarse aggregate	20% including air content
SP1	Varied, depend on s/m and air entraining agent dosage
SP2	Varied, depend on s/m and air entraining agent dosage
AE 1	Varied in dosage and produce entrained air approximately 7-13% (including entrapped air)
AE 2	Same as above
AE 3	Same as above

2.3 Mixing process

The experiments were conducted in the controlled room that temperature and relative humidity were constant as 20°c and 95% respectively. Every mix proportions were mixed by the same process, which is very strict about the time in each step. First, cement, and sand were mixed together for 30 s, and then liquid materials (water, superplasticizer and air-entraining agent) were added and mixed for 120 s. Mortar flow was measured at 5 mins in order to check initial deformability of mortar by using flow cone as shown in Fig 6. Subsequently funnel test and measuring air content by air meter (pressure method) were performed. Mortar flow test was performed again at 20 mins. Mortar must satisfy the proper mortar, which flow cone is in range 255 to 275 mm, otherwise mix proportion will be adjusted and mix from the first step until it satisfies cone flow range. Once the proper mortar was achieved, the funnel test of mortar was performed, then model coarse aggregate was put to mortar and stirred for 20 times by scoop as shown in Fig. 7. Through this step, air content reduced approximately 1.0% according to another researcher's investigation that air content in mortar reduced approximately 1.0% at first 30mins, even using SP1 or SP2 or AE1, AE2 and AE3. Finally, funnel test of mortar with model coarse aggregate was performed. Model coarse aggregate was added 20% by volume of mortar, which is the suitable for funnel test for mortar. Finally, mortar mix was repeated 2 more times for confirming the deviation of data. Mixing process is shown in Fig. 8.

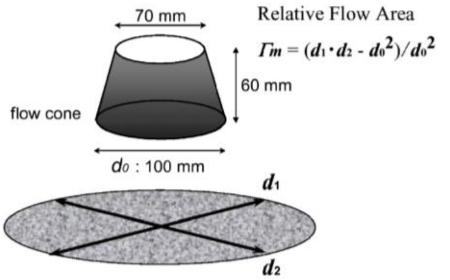


Fig. 6 Mortar flow test [5]

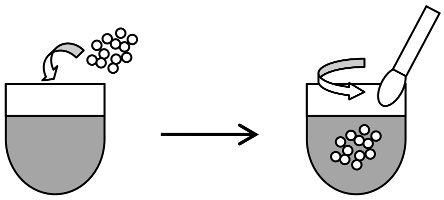
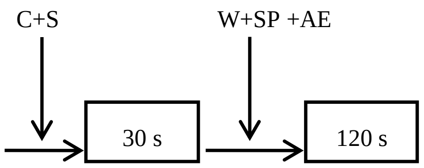


Fig. 7 Adding model coarse aggregate to mortar



C : cement S : sand AE : air entraining agent

W : water SP: superplasticizer

Fig. 8 Mixing process

The degree of the interaction between coarse aggregate and mortar ($1-R_{mb}/R_m$) depend on materials used in mix proportions, as shown Fig. 4. Tendency of the increase in $1-R_{mb}/R_m$ is almost linear relation, which is increased due to the increase in s/m. In cases of mix proportions used ordinary portland cement, $1-R_{mb}/R_m$ was reduced by using land sand instead of river sand and crushed stone sand. However in case of mix proportions used fly ash, tendency of results between mix proportions used crushed stone sand and river sand are very close. Furthermore, there is slightly difference between mix proportions used ordinary portland cement and fly ash, considered the same fine aggregate used in mixes.

To verify results of mortar to concrete, mix proportions of mortar were mixed with real coarse aggregate and tested flowability of concrete by box test. Although each mix proportions used different type of fine aggregate, but the tendency of results were almost the same, as shown in Fig. 5. It can be said that the degree of interaction between coarse aggregate and mortar can be preliminary used to predict the flow height of SCC, which is represented the self-compactibility of SCC.

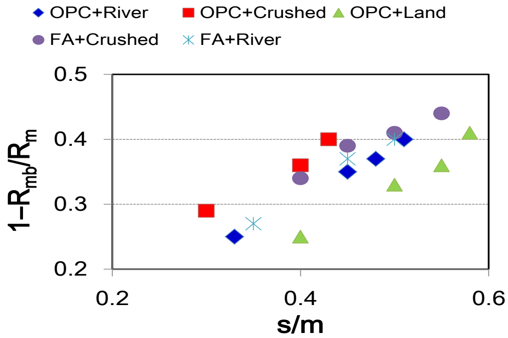


Fig. 4 Degree of the interaction between coarse aggregate and mortar ($1-R_{mb}/R_m$) in accordance with sand to mortar ratio (s/m) of mix proportions used various types of powder material and fine aggregate

OPC : Ordinary Portland cement River : River sand

Crushed : Crushed stone sand Land : Land sand

FA: Fly ash

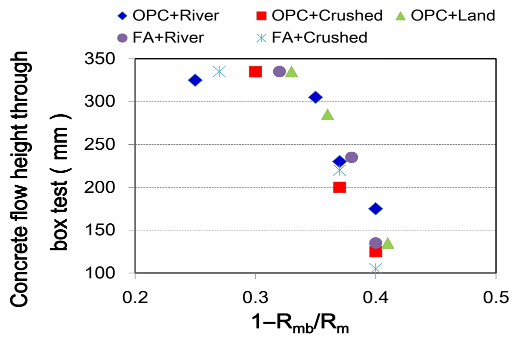
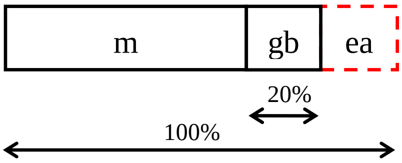


Fig. 5 Relationship between concrete flow height through box test and degree of interaction between coarse aggregate and mortar

3. RESULTS AND DISCUSSION

3.1 Calculation of volume of model coarse aggregate including volume of air on $1-R_{mb}/R_m$ (volume of glass beads was calculated including volume of air)

Truly, volume of mortar increased due to the increase in volume of paste by entrained air, called volumetric increase in paste by entrained air. Hence in these mix proportions, volume of air was measured first, and then volume of glass beads was calculated based on actual volume of mortar by including actual volume of air in mortar as shown in Fig. 8. By this method, volume of glass beads was maintained as 20%, although volume of air was any value. Therefore reduction in volume of glass beads by increasing volume of mortar by entrained air was eliminated. Accordingly, 3 types of air entraining agent were employed in order to study ball bearing effect by entrained air produced by different type of air entraining agent.



m : Volume of mortar, ea : Volume of entrained air

gb : Volume of glass beads

Fig. 8 Volume of glass beads including volume of air

3.2 Results of the mitigation on interaction between coarse aggregate and mortar ($1-R_{mb}/R_m$), using conventional type of superplasticizer (volume of glass beads was calculated including volume of air)

Mix proportions using conventional type of superplasticizer are shown in Table 3.

Table 3 Mix proportions used convention type of superplasticizer

Original s/m	Type of AE	s/m (including volume of air) (%)	Volume of air (%)
50	Without AE	48.9	2.3
55	AE 1	48.7	13.0
55	AE 2	49.1	12.0
53	AE 3	49.1	8.0
45	Without AE	44.1	1.9
50	AE 1	45.5	10.0
50	AE 2	44.5	12.3
48	AE 3	44.7	7.3

Fig. 9 shows relationship between the degree of interaction between coarse aggregate ($1-R_{mb}/R_m$) and mortar and sand to mortar ratio (s/m). It can be seen that $1-R_{mb}/R_m$ was increased due to the increase in s/m. In this research, no shrinkage of entrained bubbles according to compression by approaching coarse aggregate particles during the deformation of concrete was assumed. In case of s/m including air content was approximately 45%. The $1-R_{mb}/R_m$ of mix proportions without entrained air, with AE 1, with AE 2 and with AE 3 were almost the same as approximately 0.4. It can be said that low s/m including air content caused high distance between sand particles, resulting in low density of entrained air between sand particles as shown in Fig. 10. Hence $1-R_{mb}/R_m$ depended mainly on properties mortar, properties of mortar of these 4 mixes are the same, resulting in very close value of $1-R_{mb}/R_m$. On the other hand, the difference in $1-R_{mb}/R_m$ by using different type of air entraining agent was observed in case of s/m was approximately 49%. The $1-R_{mb}/R_m$ was 0.358, which was the lowest among other mixes by mean of AE 3. And AE 1 shows negative effect on $1-R_{mb}/R_m$, which was higher than that mix of proportion without AE. The $1-R_{mb}/R_m$ of mix proportion without AE and Mix proportion with AE 1 were 0.426 and 0.480 respectively. By using AE 2, the $1-R_{mb}/R_m$ was almost the same as mix without AE, which was approximately 0.425. No advantage on $1-R_{mb}/R_m$ was found in mix proportions using AE 1 and AE 2. Basically, the degree of interaction between coarse aggregate and mortar is increased due to the increase in sand content. The $1-R_{mb}/R_m$ can be maintained by using AE 3 in mix. Therefore ball bearing effect was existed by using AE 3.

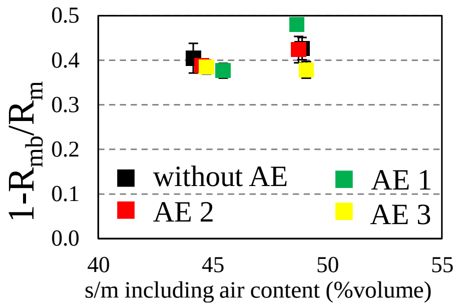


Fig 9. Effect of entrained air on $1-R_{mb}/R_m$ by using SP1, glass beads including volume of air

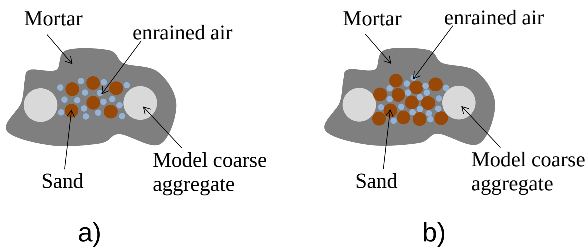


Fig 10. Effect of entrained air on distance between sand particles a) high distance (low s/m), b) low distance (high s/m)

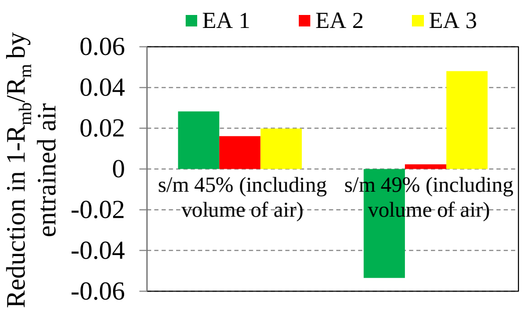


Fig 11. Degree of mitigation of $1-R_{mb}/R_m$ by using various type of AE and SP1, comparing to mix without AE

Fig. 11 shows the degree of mitigation of interaction between coarse aggregate and mortar ($\Delta 1-R_{mb}/R_m$) by using AE 1, AE 2 and AE 3 with superplasticizer SP1, comparing mix without air entraining agent. In case of s/m of approximately 45%, the degree of mitigation of

$1\text{-}R_{mb}/R_m$ by ball bearing effect was observed. Entrained air produced by 3 types of AE enhanced ball bearing effect. The degree of mitigation was approximately 0.2, this value was quite less for increasing s/m in concrete matrix. In case of s/m of approximately 49%, the degree of mitigation was approximately 0.05 with AE 3. Conversely, negative effect on ball bearing effect was found in mix using AE 1. And no significant results by using AE 2 have been found.

3.3 Results of the mitigation on interaction between coarse aggregate and mortar ($1\text{-}R_{mb}/R_m$), using new type of superplasticizer (volume of glass beads was calculated including volume of air)

Mix proportions used new type of superplasticizer are shown in Table 4.

Table 4 Mix proportions used convention type of superplasticizer

Original s/m	Type of AE	s/m (including volume of air)(%)	Volume of air (%)
50	Without AE	48.7	2.7
56	AE 1	50.1	11.7
55	AE 2	49.5	11.2
53	AE 3	49.1	8.0
47	Without AE	46.4	1.4
50	AE 1	45.5	10.0
50	AE 2	45.6	9.5
49	AE 3	45.9	6.7

Fig. 12 shows the ball bearing effect by entrained air of mix proportion using SP2. In case of s/m was approximately 45%, ball bearing effect was very effective on $1\text{-}R_{mb}/R_m$ by using AE 1, compared with mix proportion without AE. The $1\text{-}R_{mb}/R_m$ of mix used AE 1 was approximately 0.255. And the $1\text{-}R_{mb}/R_m$ of mix proportion by using AE 2 and AE 3 were very close to mix proportion without AE, which were approximately 0.340. Combination of new type of superplasticizer and AE 1 was effective for mix proportions which contain s/m including air content approximately 45%. However, no advantage on $1\text{-}R_{mb}/R_m$ in case of s/m including air content was approximately 49% has been found in mix proportion used AE 1, comparing to mix without AE. In case of s/m was approximately 49%, $1\text{-}R_{mb}/R_m$ was approximately 0.358 which was lowest by using AE 3, compared with the other mixes. The $1\text{-}R_{mb}/R_m$ of mix proportions used AE 1, AE 2 and mix without AE were 0.435, 0.472 and 0.432 respectively. Furthermore, s/m with air content of approximately 53% to 54%, were tried in order to observe the effect of ball bearing effect in case of very high sand to mortar ratio (sand to mortar ratio over 50%). Mix proportion used AE 1 and mix without AE could not be tested by mortar funnel test because the original s/m was large and ball bearing effect was not effective enough to enhance the mortar passed through the funnel tool. However mix proportion used AE 2 and AE 3 could be tested. The $1\text{-}R_{mb}/R_m$ of mix proportion used AE 2 and AE 3 were 0.571 and 0.501 respectively, which is not a good value for achieving SCC, but AE 3 still showed better results on $1\text{-}R_{mb}/R_m$, compared with AE 2.

In addition, the degree of interaction between coarse aggregate and mortar of mix proportions used new type of superplasticizer were lower than that of mixes used conventional type of superplasticizer. New type of superplasticizer contains viscosity agent, this may resulted in producing better properties of entrained air bubbles such as diameter of bubbles, toughness of bubbles or resistance to shrinkage.

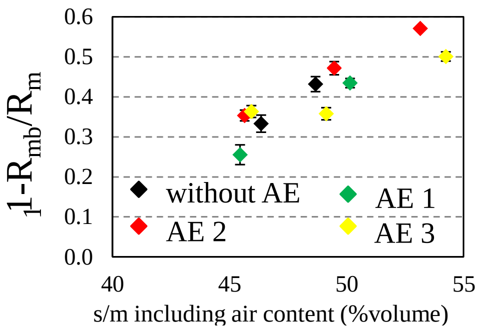


Fig 12. Effect of entrained air on $1\text{-}R_{mb}/R_m$ by using SP2, glass beads including volume of air

According to overall results of mixes using SP1 and SP2, tendency of results were different, considered mixes using same type of AE. The interaction between coarse aggregate and mortar increased due to the increase in s/m, except mixes using AE 3 because AE3 produced bubbles which have suitable properties for both mixes (s/m 45% and 49%). SP2 contains viscosity agent in itself, this may resulted in production of good characteristic of bubbles such as diameter of bubbles, toughness of bubbles and resistance to shrinkage. Entrained bubbles which produced by SP2 was effective on ball bearing effect, especially in case of long distance between sand particles (s/m of approximately 45%). In cases of s/m of approximately 49%, the interaction between coarse aggregate and mortar were slightly different, comparing to mixes using SP1, except mixes using AE2. However, SP2 mainly showed good results on interaction between coarse aggregate and mortar, resulted in the different in tendency of data, comparing to mixes using SP1.

Fig. 13 shows the degree of mitigation of interaction between coarse aggregate and mortar ($\Delta 1\text{-}R_{mb}/R_m$) by using 3 types of AE with superplasticizer SP2, comparing to mixes without air entraining agent. In case of s/m of approximately 45%, $\Delta 1\text{-}R_{mb}/R_m$ by using AE 1 was 0.08, which was very high. AE 2 and AE 3 showed negative results on ball bearing effect. On the other hand, in case of s/m is approximately 49%, the degree of mitigation of $1\text{-}R_{mb}/R_m$ reduced approximately 0.08 by using AE 3. And negative results were observed by using AE 1 and AE 2. It can be said that AE 3 enhanced effectively the degree of mitigation of $1\text{-}R_{mb}/R_m$, in case of high s/m. This resulted in the increase in sand content in mix proportion.

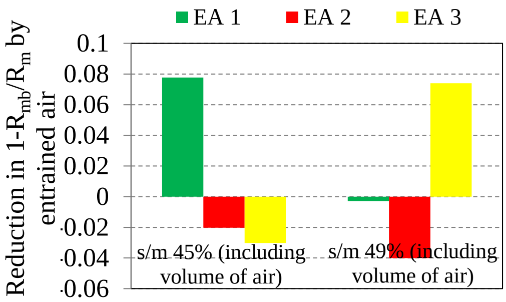


Fig 13. Degree of mitigation of $1\text{-}R_{mb}/R_m$ by using various type of AE and SP2, comparing to mix without AE

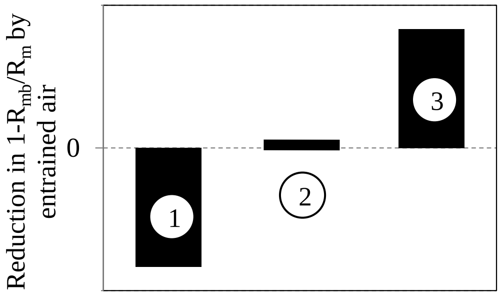


Fig 14. The reduction in $1\text{-}R_{mb}/R_m$ with entrained air, comparing to mix without AE

3.4 Discussion

Total volume of mortar increased due to the increase in entrained air in cement paste. This resulted in consequent reduction in sand to mortar ratio (s/m). Furthermore, volume of model coarse aggregate was fixed as 20% of volume of mortar at mix design step (excluding air content), therefore model coarse aggregate to mortar ratio was reduced after mixing as well. Accordingly, the volume of solid in mortar reduced according to the increase in entrained air content, resulted in reduction in the interaction between coarse aggregate and mortar ($1\text{-}R_{mb}/R_m$). This is called "volumetric increase in paste effect"

Ball bearing effect by entrained air could be observed by following calculation method in section 3.1. Entrained air content was aimed and s/m including air content could be calculated from original s/m. Volume of model coarse aggregate was adjusted to be 20% of volume of mortar according to the increase in air content. By this method, effect of the presence of entrained air, which is called "Ball bearing effect", was observed by comparing to mix without entrained air.

Effect of entrained air on reduction in 1 $-R_{mb}/R_m$ was classified into 3 types, as shown in Fig. 14. By assuming that friction of cement paste is higher than that of air, entrained air may enhance the reduction in $1\text{-}R_{mb}/R_m$. Model coarse aggregate volume was adjusted to be 20% in accordance with the increase in air content. Bar No.1 means negative result on reduction in $1\text{-}R_{mb}/R_m$. This may be due to the shrinkage of bubbles, resulted in the increase in sand to mortar (s/m) and model coarse aggregate to mortar ratio consequently. Therefore, the interaction between coarse aggregate and mortar was increased due to the increase in solid particles in matrix. Bar No.3 means positive effect on reduction in $1\text{-}R_{mb}/R_m$ by entrained air, which could be explained that the characteristic of air bubbles were appropriate to resist shrinkage of bubbles and bubbles worked as ball bearing simultaneously. Bar chart No.2 means no effect on reduction in $1\text{-}R_{mb}/R_m$. In this case, there are 2 possible assumptions that are entrained bubbles were not shrunk, but those bubbles did not work as ball bearing, or shrinkage partially occurred, but entrained bubbles were suitable for ball bearing effect.

4. CONCLUSIONS

According to the results and discussion, conclusions can be written as follow.

(1) The authors have set up 2 types of mechanism on entrained air on interaction between coarse aggregate and mortar which were volumetric increase in paste and ball bearing effect.

(2) The degree of interaction between coarse aggregate and mortar ($1\text{-}R_{mb}/R_m$) could be obtained from this test method. And this index could be used to evaluate the effect of volumetric increase in paste and ball bearing effect by entrained air.

(3) Effect of volumetric increase in paste with entrained air was observed in the mortar even subject to normal stress by coarse aggregate.

(4) Ball bearing effect by entrained air was observed in the mix proportion using AE 3 with both of conventional type and new type of superplasticizer in cases of sand to mortar ratio of approximately 49% (including air content). And by using AE 1, ball bearing effect was observed in mix proportions using both types of superplasticizer with sand to mortar ratio of approximately 45% (including air content).

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