- Technical Paper -

BALL-BEARING EFFECT OF FLY ASH FOR HIGHER FINE AGGREGATE CONTENT IN SELF-COMPACTING CONCRETE

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ABSTRACT

The effect of fly ash on self-compactability of fresh concrete for increasing fine aggregate content (*s*/*m*) in self-compacting concrete (SCC) was investigated. Both reduction in water retention and ball-bearing effect of fly ash were considered as the influence of the replacement of cement with fly ash. Higher *s*/*m* in SCC can be employed as fly ash replacement ratio (*fa*/*p*) increases owing to the higher ball-bearing effect of fly ash, in spite of reduction in water to powder ratio (*w*/*p*). Besides, with certain *fa*/*p* and reduction in *w*/*p*, decrease in 28 days compressive strength tended to be mitigated.

Keywords: self-compacting concrete, self-compactability, fly ash, ball-bearing effect, water retention, fine aggregate content, compressive strength.

1. INTRODUCTION

Self-compacting concrete (SCC) was initially developed in 1988 to enhance concrete durability without the requirement of skilled labour [1]. In order to achieve adequate self-compactability, suitable deformability and viscosity of the mortar and paste phase in SCC is necessary. Generally, the self-compactability of SCC can be attained by limiting the aggregate content, using low water-powder ratio and employing superplasticizer [1]. Hence, SCC usually requires higher cement content and dosage of superplasticizer, comparing to conventional concrete, which leads to considerably higher cost (Fig. 1).

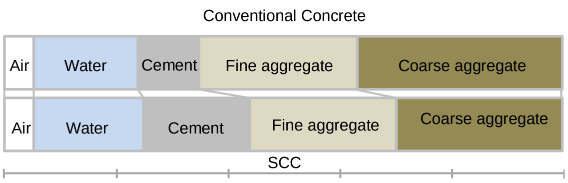

Fig.1 Comparison between self-compacting concrete (SCC) and normal concrete volumetric mixture proportion

Currently, many types of supplementary cementitious material (SCM) are being employed into concrete to reduce the usage of cement for economical purpose such as fly ash. Since fly ash is considered as a by-product of coal burning in a power plant, its utilization is desirable. Although fly ash generally tends to reduce compressive strength of concrete, required concrete strength can still be achieved with appropriate replacement ratio [2-4]. This attributes to fly ash chemical reactions including pozzolanic and hydration reaction. Subsequently, fly ash is widely introduced into SCC due to its low cost and high performance as SCM [5, 6]. Up to now, the effects of fly ash on fresh and hardened properties of self-compacting concrete have been intensely studied [4, 5, 7-14]. Nonetheless, these studies tend to replace cement with fly ash directly, without increasing the aggregate content, as well as replacing aggregate with fly ash. In this paper, the ball-bearing effect of fly ash on the self-compactability of SCC is studied to increase the fine aggregate content for further cost reduction.

2. TESTING METHOD AND INDICES USED FOR EVALUATING EFFECT OF FLY ASH ON SELF-COMPACTABILITY OF SCC IN FRESH MORTAR

2.1 Indices for evaluating flowability of fresh mortar

Fly ash had been shown to influence flowability of SCC by its ball-bearing effect and reduction in water demand due to its spherical shape [7, 15]. This includes the change in deformability and viscosity of fresh mortar and hence the self-compactability of SCC. The mortar flow and funnel tests were used to determine the deformability and viscosity of the fresh mortar respectively (Fig.2). The deformability of the fresh mortar is obtained in terms of relative flow area, Γm, while its viscosity was quantified in terms of relative funnel speed, Rm.

The relationship of the reduction in retained water (β_{WP}) and increase in unit free water (E_{WP}) with the higher fly ash replacement ratio (*fa*/*p*) had already been clarified by evaluating deformability and viscosity of the fresh mortar [7]. It had been illustrated that amount of free water in fresh mortar ($Rm/\Gamma m^{0.4}$) has a

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linear correlation with *w*/*p* and can be used to determine the retained and unit free water [16]. The retained water (β_{WP}) can be described as the minimum *w*/*p* required for the mortar to start flowing, which is obtained by the intercept of *w*/*p* and $Rm/\Gamma m^{0.4}$ relation. Correspondingly, the unit free water (E_{WP}) can be expressed as the additional w/p reducing the viscosity of the fresh mortar, which is the inclination of the *w*/*p* and $Rm/\Gamma m^{0.4}$ relation.

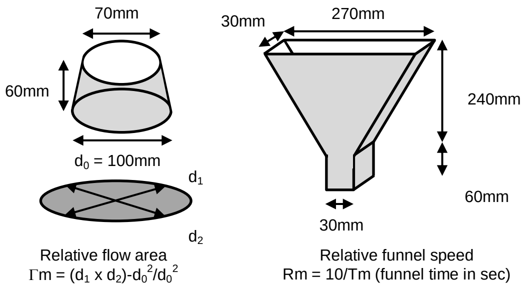

Fig.2 Mortar flow cone test (Left) and mortar V-funnel test (Right)

2.2 Simple evaluation method for self-compactability of SCC in fresh mortar

Since testing the self-compactability in SCC requires high numbers of labor, a simple evaluation method for self-compactability of SCC in fresh mortar had been developed [17]. This method involves an employment of model coarse aggregate in the fresh mortar testing. Glass bead was found to be effective for being used as model coarse aggregate to evaluate the self-compactability of SCC in fresh mortar [17]. The self-compactability of SCC was determined in term of the relative funnel speed of the fresh mortar, Rm, and fresh mortar with glass beads, Rmb (Fig.3). The self-compactability of SCC was found to be correlated with the degree of reduction in flowability of mortar due to the model coarse aggregate, 1-(Rmb/Rm).

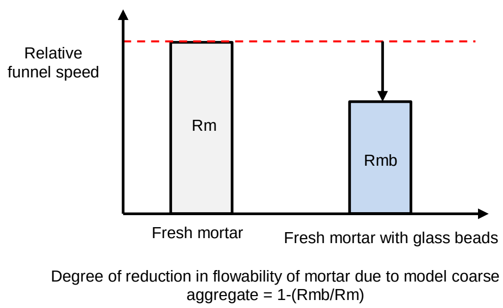

Fig.3 Reduction in flowability of mortar due to the model coarse aggregate

The self-compactability of SCC, with the same coarse aggregate's physical properties and content, had been found to be influenced by the variety in mortar mix proportions and materials used [16]. The index, 1-(Rmb/Rm), was developed to evaluate of self-compactability of SCC in fresh mortar with various mixture proportions [17]. The verification of the evaluation method has shown a unique correlation between the index 1-(Rmb/Rm) and filling height of the concrete Box test (Fig.4). The concrete Box test with obstacle R1 (Five D10 deformed bars) were used for the verification (Fig.5). This relation was shown between fresh mortar with 20% glass beads and SCC with standard coarse aggregate content of 30% [17].

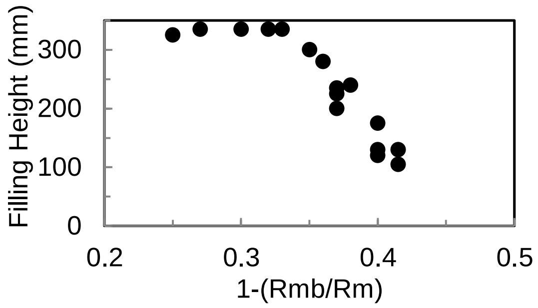

Fig.4 Relationship between the degree of reduction in flowability of mortar due to the model coarse aggregate (1-(Rmb/Rm)) and self-compactability (Concrete filling height) [18]

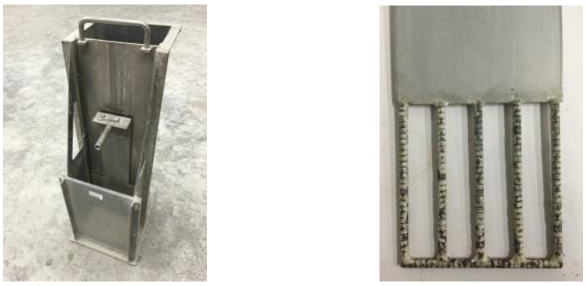

Fig.5 Concrete Box test (Left) and obstacle R1 (Right)

2.2 Testing method for evaluating effect of fly ash on flowability and self-compactability of SCC in fresh mortar

(1) Materials

The powder materials used in this experiment were cement and fly ash. Ordinary Portland cement (OPC) was considered in this experiment and fly ash class 1 according to Japanese Industrial Standard, JIS A 6201, was employed. Superplasticizer (SP) used is commercially named as 6500 form BASF, which is polycarboxylate-based blended with viscosity modifying agent (VMA). This SP was used to enhance the stability of SCC. The fine aggregate (FA), model coarse aggregate (MCA) and coarse aggregate (CA) used were limestone (LS), glass beads and crushed stone (CS), respectively. The properties of the solid materials used in this experiment are presented in Table 1. The spherical shape of fly ash used in this experiment is shown in Fig. 6.

Table 1 Properties of materials used

Materials	Type	Specific gravity	Fineness (cm^2/g)	LOI (%)	F.M.
Powder materials	OPC (JIS R5210)	3.15	3490	1.96	-
	Fly ash I (JIS A6201)	2.40	5500	1.90	-
FA	Limestone	2.68	-		2.90
CA	Crushed stone (Max. size: 20mm)	2.70	-		6.70
MCA	Glass beads	2.54	Diameter: 10mm		

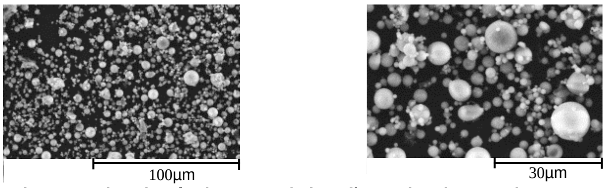

Fig.6 Spherical shape of the fly ash shown in SEM image with the magnification of 1000x (Left) and 2500x (Right)

(2) Mixing method and testing

Mixing steps and details for mortar and concrete are shown in Table 2. Since these mixing steps are found to be effetive in air-entraining SCC, they were used in case of further air-entrainment [18].

Table 2 Mixing steps and details

Type	Mixing method
Mortar	Mixer : According to JIS R5201 Batch volume : 1.68 litre Powder + Fine aggregate → (30 sec) Water 1 (63% of powder volume) + SP → (60 sec) Water 2 → (60 sec) End
Concrete	Mixer : According to JIS A8603 Batch volume : 25 litre Powder + Aggregate → (30 sec) Water 1 (63% of powder volume) + SP → (90 sec) Water 2 → (90 sec) End

The tests conducted for fresh properties of mortar and concrete in this experiment were carried out to evaluate the self-compactability of SCC. All mortar and concrete testing procedures conducted in this experiment are presented in Table 3. The mortar testing was repeated for 3 times to obtain the average results for each mortar mixture proportion, while concrete testing was performed a single time for each concrete mixture proportion.

Table 3 Testing procedures

Type	Testing procedures: Initial state	Testing procedures: At 20 minutes
Mortar	- Mortar flow test - Mortar V-funnel test - Air measurement (Gravimetric method)	- Remix for 5 sec. - Mortar flow test - Mortar V-funnel test - Air measurement (Gravimetric method) - Mortar with glass beads V-funnel test
Concrete	- Concrete slump flow test - Air measurement (Gravimetric and pressure method) - Concrete V-funnel test - Concrete Box test - Cylinder samples preparation for 28 days compressive strength	-

3. REDUCTION IN WATER TO POWDER RATIO FOR PREVENTING SEGGREGATION IN SCC WITH FLY ASH

Mortar mixture proportions, M1, M2 and M3 were tested and analyzed to explain the effects of fly ash on the flowability of SCC (Table 4). The water to powder ratio (*w*/*p*) was also varied for the amount of free water ($Rm/\Gamma m^{0.4}$) in every mortar mixture proportions with fly ash was equal to that of mortar without fly ash. Since Γm of every mortar mixture proportions was controlled to be in the same range of 5.5 to 6.6, mortar with the same Rm was considered to have the same amount of free water ($Rm/\Gamma m^{0.4}$).

Table 4 Mortar mixture proportions and measured properties at 20 minutes

Mix	Mix proportion (kg/m^3): Cement	Fly ash	Water	LS	SP/P (%)	Measured properties at 20 min.: Mortar flow (mm)	Tm (s)	Tmb (s)
M1	749	-	262	1340	2.13	260	5.84	10.27
M2	564	141	262	1340	1.15	266	3.22	5.18
M3	392	272	262	1340	0.81	266	2.47	3.65
M4	600	150	247	1340	1.34	262	5.84	9.79
M5	430	299	239	1340	1.02	270	5.77	9.30
M6	282	423	234	1340	0.88	267	5.97	9.08
M7	674	-	236	1474	3.01	257	14.04	33.21
M8	394	274	211	1474	1.16	268	13.55	24.45
M9	258	387	207	1474	0.86	261	13.03	21.91

Considering mortar with the same *w*/*p* of 1.10 and *s*/*m* of 0.50, fly ash tends to increase the amount of free water ($Rm/\Gamma m^{0.4}$) as Rm increases with *fa*/*p* as presented in Fig. 7. This suggests the enhancement in flowability of SCC due to the larger relative distance between fine aggregate and the ball-bearing effect produced by fly ash [7]. However, the larger relative distance between fine aggregate caused by the higher Rm may lead to lower segregation resistance of SCC and, hence, reduce its self-compactability.

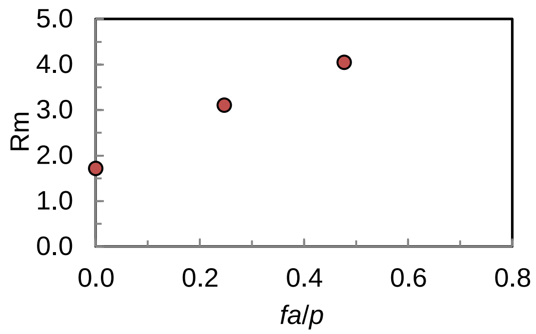

Fig.7 Increase in Rm with respect to higher *fa*/*p* and constant *w*/*p*

In order to reduce the chance of segregation in SCC with fly ash, *w*/*p* was reduced for maintaining Rm. Fig. 8 illustrates the lower required *w*/*p* for the fresh mortar to have certain value of Rm, when higher *fa*/*p* has been employed. This can be attributed to the reduction in water retention of fly ash as suggested. The reduction in the required *w*/*p* also found to have a non-linear relationship to the replacement ratio with fly ash. This may be due to the effect of SP used. Since the used SP is polycarboxylate-based blended with VMA, its dosage can influence the Rm.

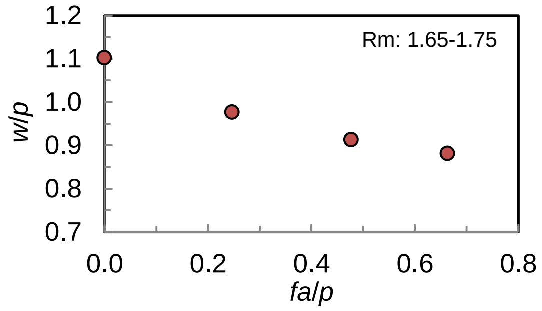

Fig.8 Reduction in *w*/*p* for keeping the level of Rm, with respect to higher *fa*/*p*

4. REDUCTION IN THE INTERACTION BETWEEN MODEL COARSE AGGREGATE AND MORTAR MATRIX IN SCC DUE TO THE BALL-BEARING EFFECT OF FLY ASH

The results obtained from mortar tests were evaluated to clarify the effects of fly ash on the self-compactability of SCC. As mentioned, fly ash was found to reduce the water demand and produce the ball-bearing effect in the mortar phase due to its spherical shape [7]. The influence of these effects on the self-compactability of SCC was quantified in terms of 1-(Rmb/Rm).

The results show that the index, 1-(Rmb/Rm), reduces, in the mortar with the same *w*/*p*, when the *fa*/*p* increases (Fig.9). The reduction in 1-(Rmb/Rm) suggests a lower interaction between the model coarse aggregate and the mortar matrix when fly ash has been employed. This may attribute to the reduction in friction and larger distance between the model coarse aggregate due to higher amount of free water. Besides, the reduction in friction between the model coarse aggregate can be caused by the ball-bearing effect of fly ash. Hence, considerable enhancement in self-compactability of SCC is indicated in fresh mortar testing, regardless the lower segregation resistance.

The index, 1-(Rmb/Rm), of the fresh mortar with the same Rm was also obtained. The results present the reduction in the index, 1-(Rmb/Rm), in spite of reduction in *w*/*p*, when *fa*/*p* increases (Fig.9). Since these series of mortar, with certain *s*/*m*, is considered to have the same $Rm/\Gamma m^{0.4}$, the relative distance between aggregate is equal. Consequently, the reduction in the index, 1-(Rmb/Rm) can be explained by the ball-bearing effect of fly ash on the model coarse aggregate (Fig.10). This effect can be attributed to the spherical shape of fly ash, which leads to the reduction in shear force from the interaction between the fine aggregate, as well as the model coarse aggregate, and the paste phase [1].

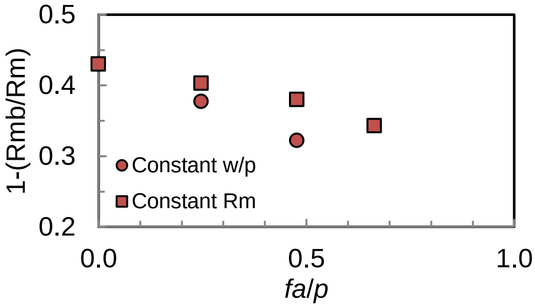

Fig.9 Reduction in 1-(Rmb/Rm) with respect to higher *fa*/*p*, in spite of the reduction in *w*/*p*

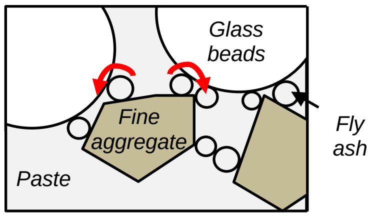

Fig.10 Ball-bearing effect of fly ash on model coarse and fine aggregate

5. BALL-BEARING EFFECT OF FLY ASH FOR REDUCTION IN THE INTERACTION BETWEEN MODEL COARSE AGGREGATE AND MORTAR MATRIX IN HIGHER FINE AGGREGATE CONTENT

The ball-bearing effect of fly ash on the self-compactability of SCC with higher *s*/*m* was quantified in terms of 1-(Rmb/Rm). The results indicate a lower range of Rm in fresh mortar with higher *s*/*m* of 0.55 (Fig.11). Despite the lower amount of free water ($Rm/\Gamma m^{0.4}$), the lower Rm of the mortar with *s*/*m* of 0.55 can be contributed to the higher stress on the past phase by the fine aggregate, when comparing with the mortar with *s*/*m* of 0.50. This higher stress is attributed to the smaller distance between the fine aggregate as *s*/*m* in the fresh mortar increases. Fig.11 has also shown a greater reduction of 1-(Rmb/Rm) in the fresh mortar with higher *s*/*m*. This may be due to the ball-bearing effect of fly ash on the mortar matrix of SCC which tends to be more effective when the distance between fine aggregate is smaller. Subsequently, higher contact between fly ash and fine aggregate can be occurred. Besides, the results have suggested that with *fa*/*p* of 0.48, 1-(Rmb/Rm) has been reduced to the similar level as that of the fresh mortar with lower *s*/*m* and without fly ash. Moreover, with higher *fa*/*p*, 1-(Rmb/Rm) has been further decreased to a lower value.

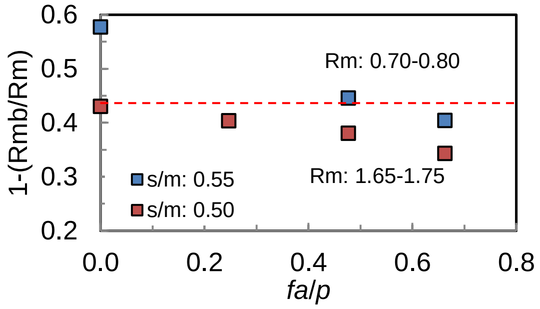

Fig.11 Similar level of 1-(Rmb/Rm) in fresh mortar with *s*/*m* of 0.50 and 0.55 with and without fly ash, respectively

6. VERIFICATION OF BALL-BEARING EFFECT AND PRACTICABILITY OF FLY ASH IN SCC

Certain mortar mixture proportions were chosen to be verified with the concrete testing for evaluating the ball-bearing effect of fly ash on self-compactability of SCC (Table 5).

Table 5 Mortar mixture proportions and measured properties

Mix	Mix proportion (kg/m^3)						Measured properties.		
	Cement	Fly ash	Water	LS	CS	SP/P (%)	Slump flow (mm)	Funnel time (s)	Filling height (s)
C1	524	-	184	938	810	1.90	260	5.84	10.27
C2	301	209	167	938	810	0.82	266	2.47	3.65
C3	197	296	164	938	810	0.65	266	2.47	3.65
C4	472	-	165	1032	810	2.81	262	5.84	9.79
C5	276	192	148	1032	810	0.96	270	5.77	9.30
C6	181	271	145	1032	810	0.80	267	5.97	9.08

The results obtained have illustrated a similar relationship between 1-(Rmb/Rm) from the mortar testing and the filling height from the concrete Box test, when comparing with the previous data [1] (Fig.12). Fig.12 suggested that in spite of the reduction in *w*/*p*, the ball-bearing effect of fly ash can effectively enhance the concrete filling height and, hence, the self-compactability of SCC.

The results of the concrete with *s*/*m* of 0.50 have shown that as *fa*/*p* increases from 0 to 0.48, the filling height has developed from 88mm to the 290mm, which is higher than the desirable level of 250mm, respectively (Fig.12). The further increase in *fa*/*p* to 0.66 also improves the filling height of the concrete to 255mm. Slight reduction in filling height has been notified as *fa*/*p* increase from 0.48 to 0.66 (Fig.12). This may be due to the slight variation of the sand properties in the same batch.

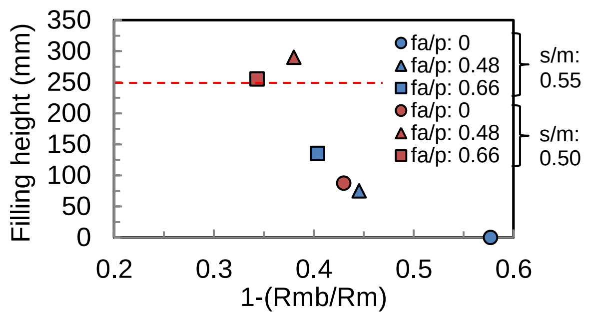

Fig.12 Increase in degree of self-compactability due to ball-bearing effect of fly ash

Similar relationship between 1-(Rmb/Rm) and the filling height has also been indicated by the results of the concrete with *s*/*m* of 0.55. Although the concrete filling height reaches only 135mm with *fa*/*p* of 0.66, this concrete might be able to reach 250mm in less severe concrete Box test with obstacle R2.

Furthermore, in spite of the reduction in *w*/*p*, fly ash can reduce the required SP/P as presented in Fig.13. Since these concrete mixture proportions are considered to have the same amount of free water, the reduction in SP/P required may be attributed to the ball-bearing effect of fly ash. Beside this, fly ash itself has a weaker adsorbing capacity than cement as it is negatively charged [19].

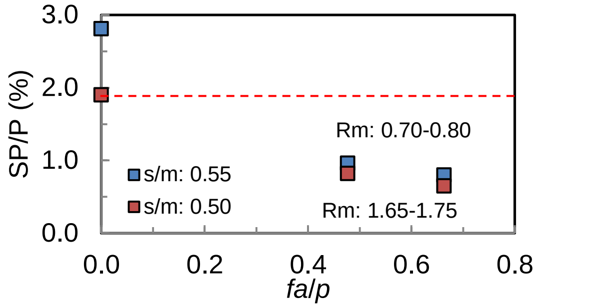

Fig.13 Lower SP/P required in SCC with *s*/*m* of 0.50 and 0.55 with and without fly ash, respectively

In addition to the enhancement in self-compactability, fly ash has been found to slightly affect the compressive strength of SCC. The results obtained from the concrete experiment have suggested that, in general, the compressive strength tends to reduce with respect to higher *fa*/*p* (Fig.14). However, with a suitable replacement ratio with fly ash of 0.25, the compressive strength of SCC is slightly affected. Fig.14 also shows that, with further reduction in *w*/*p*, the reduction in strength may be mitigated. Moreover, considering the same Rm, the compressive strength of SCC is still higher than 60 N/mm^2 as *fa*/*p* has been increased to up to 0.48.

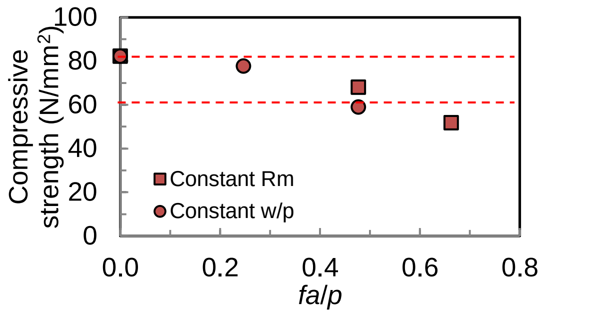

Fig.14 Effect of fly ash on compressive strength of SCC

7. CONCLUSION

The flowability of fresh mortar with various *fa*/*p* was measured and evaluated to determine the self-compactability of SCC. The superplasticizer dosage (SP/P) was altered for every mixture proportions of fresh mortar to obtain the targeted relative flow area of 5.5 to 6.6. Water to powder volumetric ratio (*w*/*p*) had also been adjusted for preventing segregation and clarifying the ball-bearing effect of fly ash. The mortar results were further verified with the concrete testing. The effects of fly ash on the self-compactability of SCC can be concluded as following:

(1) With the same *w*/*p*, fresh mortar with higher *fa*/*p* suggested reduction in 1-(Rmb/Rm). However, higher amount of free water was notified. This may lead to higher possibility of segregation.

(2) In spite of the reduction in *w*/*p* for preventing segregation, the ball-bearing effect of fly ash

showed to reduce the index, 1-(Rmb/Rm). Besides, with the increase in *fa*/*p*, 1-(Rmb/Rm) of mortar with certain *s*/*m* can be reduced to the similar level as that of mortar with higher *s*/*m*.

(3) The ball-bearing effect of fly ash was found to be more effective in the fresh mortar with higher *s*/*m*, due to smaller relative distance between the aggregate.

(4) The concrete results suggested that the ball-bearing effect of fly ash significantly increased the self-compactability of SCC and reduced the required SP/P.

(5) Compressive strength at the age of 28 days decreased with respect to higher *fa*/*p*. However, with suitable *fa*/*p*, the concrete strength was slightly affected. The further reduction in *w*/*p* tended to mitigate the reduction in strength.

The ball-bearing effect of fly ash was found to be able to allow higher *s*/*m* and reduce required SP/P in SCC. These suggest the potential of fly ash for reducing the cost and increasing the sustainability of SCC. In addition, the ball-bearing of fly ash may be used in combinations with other methods to further increase the sustainability of SCC.

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