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AIR CONTENT OF SELF-CONSOLIDATING CONCRETE AND ITS MORTAR PHASE INCLUDING RICE HUSK ASH

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Abstract. This paper presents the air content results of self-consolidating concrete (SCC) and its mortar phase including rice husk ash (RHA) as a supplementary cementing material. Moreover, this paper demonstrates a simple technique to determine the dosage of air-entraining admixture (AEA) required for the target air content in SCC. Different SCC mixtures were designed based on the water/binder (W/B) ratios of 0.30–0.50 and design air content of 4–8%. RHA was incorporated in the concretes substituting 0–30% of cement by weight. The mortars were formulated from the mixture proportions of the corresponding parent concretes and tested to determine the air content at various AEA dosages. The effects of W/B ratio and RHA content on the air content of both mortar and concrete were observed. The effect of mortar volume on the air content of concrete was also noticed. Besides, the AEA dosages required for the target air contents of concrete were estimated based on the equivalent mortar air contents. Later the air-entrained SCC mixtures were produced using AEA and tested for the air content. Test results exhibit that the air contents of both mortar and concrete were significantly influenced by the W/B ratio and RHA content. The concrete air content was also greatly influenced by its mortar volume. The AEA dosage increased with lower W/B ratio, higher RHA content, and greater mortar volume for the target air contents. In addition, the actual AEA dosages were consistent with the estimated AEA dosages of the concretes. An excellent correlation was observed between the actual and estimated AEA dosages. The strong correlation suggests that the AEA dosage needed for a target air content in concrete can be determined based on the equivalent air content of its mortar phase.

Keywords: air content, air-entraining admixture, concrete, mixture proportions, mortar, rice husk ash.

1. Introduction

Self-consolidating concrete (SCC) is relatively a new development in concrete technology. It is a highly flowing concrete that spreads under self-weight to reach each and every corner of the formwork, and is consolidated without any external means such as rodding or vibration (Khayat 1999; EFNARC 2002). SCC is a good choice for many concrete structures where placement and consolidation of ordinary concrete are complicated due to intricate formwork shape and congested reinforcing bars. It requires several additional constituent materials such as supplementary cementing material (SCM) and high-range water reducer (HRWR) in addition to the basic ingredients of ordinary concrete. SCC must need HRWR to achieve the self-consolidation capacity in fresh state (Safiuddin 2008; Safiuddin *et al.* 2010a). It can also include SCM mainly to improve the strength and durability of concrete (Safiuddin *et al.* 2010b). However, both SCC and ordinary concrete must need air-entraining admixture (AEA) to obtain entrained air content for enhanced durability or extended service life in freezing and thawing environment.

Adequately high air content (4–8%) is essential to improve the durability of concrete exposed to freezing and thawing environment (ACI Committee 318 2009; Jana *et al.* 2005; Kosmatka *et al.* 2009; Persson 2003). For this, a sufficient dosage of AEA must be used in concrete. An AEA incorporates millions of non-coalescing microscopic air bubbles in fresh concrete and forms a network of air-voids in hardened concrete. The air-voids perform as pressure releasing valves to reduce the hydraulic stresses caused by the freezing water, and thus improve the durability performance of concrete in freezing and thawing environment (Chatterji 2003; Powers 1949; Sun and Scherer 2010).

Achieving the target air content in concrete is not a straight-forward task. It is more fastidious for SCC because of its highly fluid nature and complex admixture systems. Excessive fluidity may cause air-void instability problem in SCC leading to a reduction in concrete air content (Szwabowski and Łaźniewska-Piekarczyk 2009). In addition, the air bubbles may reduce the segregation resistance of SCC by affecting its yield stress and plastic viscosity (Bonen and Shah 2005; Carlsward *et al.* 2003; Khayat 2000). When the segregation resistance is reduced, the air content of SCC consequently can be affected due to the upward movement and escape of air bubbles. The presence of HRWR also tends to destabilize the entrained air bubbles during transport and placement of concrete leading to a reduction in air content (Khayat and Assaad 2002; Safiuddin *et al.* 2006; Saucier *et al.* 1990). Furthermore, aggregate grading, cement composition, type and re-dosing of HRWR, mixing and placing methods, re-mixing of concrete, type and composition of SCM, cement-admixture compatibility, type of AEA and ambient temperature influence the air-entrainment and air-void stability in SCC (ACI Committee 201 2008; Carlsward *et al.* 2003; Du and Folliard 2005; Shetty 2007; Zhang and Wang 2005). For example, polycarboxylate-based HRWR induces additional air-voids in SCC by decreasing the surface tension of the liquid phase in paste (Szwabowski and Łaźniewska-Piekarczyk 2009). In contrast, RHA causes a loss of air-voids in SCC by increasing the yield stress and plastic viscosity of concrete (Safiuddin 2008; Safiuddin *et al.* 2006). A similar effect can be observed for other SCM. Therefore, achieving the target air content in SCC is most often problematic. A number of trial mixtures can be required to determine the AEA dosage for target air content. It may cause a significant loss of materials, labour, and construction time resulting in an uneconomical concrete production. This problem can be resolved if it is possible to estimate the AEA dosage for a target air content before concrete production.

In the present study, a number of air-entrained SCC mixtures were produced including RHA as an SCM. The effects of W/B ratio and RHA content on the air content of SCC and its mortar phase are discussed in this study. The effect of mortar volume on the concrete air content is also shown in this study. In addition, the present study demonstrates a simple technique to estimate the AEA dosage for air-entrained SCC based on the air content of its mortar phase.

2. Experimental Methods

2.1. Constituent materials

A blend of crushed and round aggregates with an equal mass was used as the coarse aggregate (CA). The fine aggregate (FA) used was natural pit sand. The aggregates had low absorption value and fines (< 75 µm) content. In addition, both fine and coarse aggregates fulfilled the ASTM C33/C33M-08 (2008) grading requirements, as can be seen from Figs 1 and 2.

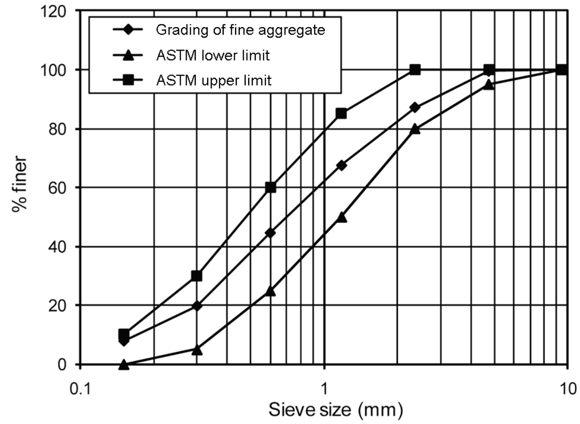

Fig. 1. Gradation of fine aggregate

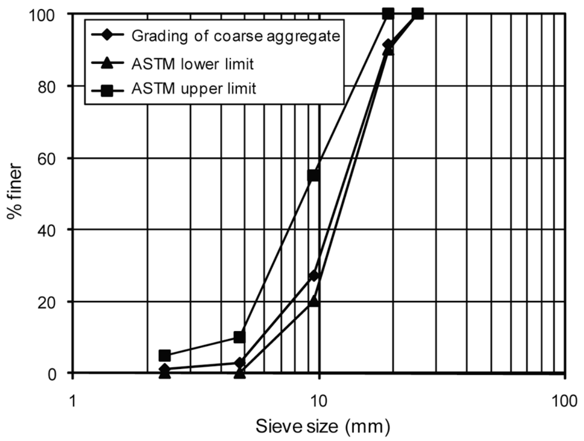

Fig. 2. Gradation of coarse aggregate

Normal portland cement (C) conforming to the ASTM C150/C150M-09 (2009) specifications was used as the main cementing material. Amorphous RHA was used as an SCM. The use of RHA widened the range of AEA dosage, since it increases the AEA demand to achieve specified air content in concrete (Safiuddin *et al.* 2006; Zhang and Malhotra 1996). Cement and RHA together acted as the binder (B). The normal tap water (W) was used as the mixing water for preparing the mortars and concretes. In addition, a polycarboxylate-based HRWR and a synthetic AEA were used to produce the required flowing ability and air content, respectively. The major physical properties of the constituent materials are given in Table 1. Most of these properties were useful to obtain the mixture proportions of mortars and concretes.

Table 1. Physical properties of constituent materials

Material	Properties
Coarse aggregate (CA)	Maximum size: 19 mm; fineness modulus: 6.78; mass passing 75-µm dry sieve: 0.8%; void content: 37%; saturated surface-dry relative density: 2.71; absorption: 1.5%; moisture content: 0.1%
Fine aggregate (FA)	Maximum size: 4.75 mm; fineness modulus: 2.74; mass passing 75-µm dry sieve: 1.8%; void content: 28%; saturated surface-dry relative density: 2.62; absorption: 1.0%; moisture content: 0.1%
Cement (C)	Relative density: 3.16; mass passing 45-µm wet sieve: 91.5%; mass passing 75-µm dry sieve: 99.1%; Blaine specific surface area: 412 m^2/kg; autoclave expansion: 0.11%
Rice husk ash (RHA)	Relative density: 2.07; Blaine specific surface area: 2326 m^2/kg; accelerated pozzolanic activity index: 122.4%
Water (W)	Density: 997.28 kg/m^3; total solids: 430 mg/l
High-range water reducer (HRWR)	Relative density: 1.07; solid content: 41%
Air-entraining admixture (AEA)	Relative density: 1.01; solid content: 13%

The particle size distributions of cement and RHA are shown in Fig. 3. This figure shows that the median particle size of RHA was 6 µm whereas that of cement was 15 µm. Moreover, it can be seen from this figure that about 98% of RHA (by mass) was finer than 45 µm. The mass finer than 45 µm was around 91% in the case of cement.

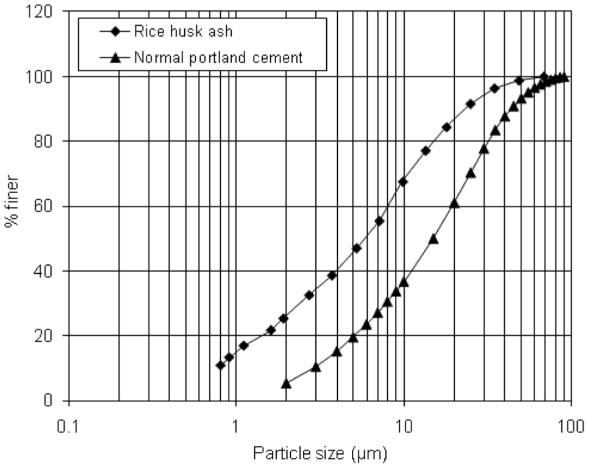

Fig. 3. Particle size distribution of cement and RHA

The chemical compositions of cement and RHA are given in Table 2. RHA had a mass-based silica content of 93.6%. It suggests that the RHA used was a highly reactive pozzolanic SCM, which is also obvious from the high accelerated pozzolanic activity index of 122.4% (refer to Table 1). The deleterious components of cement such as MgO, SO_3, and insoluble residue were below the maximum limits, as specified in ASTM C150/C150M-09 (2009). However, the equivalent alkalis of both cement and RHA were slightly higher than the maximum allowable limit of 0.6% (ASTM C150/C150M-09 2009), which was acceptable in the absence of reactive aggregates. The loss on ignition (LOI) was below the maximum permissible limit of 3% (ASTM C150/C150M-09 2009) for both cement and RHA. Also, the RHA possessed a very low carbon content of 0.15% (by mass), which had a negligible impact on the air entrainment in mortars and concretes.

Table 2. Chemical compositions of cement and RHA

Chemical component	Mass content (%)	
	Cement	RHA
Silicon dioxide or silica (SiO_2)	19.7	93.6
Aluminum oxide or alumina (Al_2O_3)	5.1	0.02
Iron oxide (Fe_2O_3)	2.5	0.80
Calcium oxide or lime (CaO)	62.3	0.38
Magnesium oxide or magnesia (MgO)	3.3	0.34
Sulfur trioxide or sulfuric anhydrite (SO_3)	2.9	---
Sodium oxide (Na_2O)	---	0.05
Potassium oxide (K_2O)	---	1.26
Equivalent alkalis ($Na_2O + 0.658\ K_2O$)	0.72	0.88
Titanium oxide (TiO_2)	---	0.01
Phosphorous oxide (P_2O_5)	---	0.58
Manganese oxide (MnO)	---	0.14
Chromium oxide (Cr_2O_3)	---	0.01
Vanadium oxide (V_2O_5)	---	< 0.01
Free lime (FCaO)	1.1	---
Sulfur (S)	---	< 0.01
Carbon (C)	---	0.15
Others:		
Loss on ignition (LOI)	2.7	1.9
Insoluble residue	0.46	---

2.2. Concrete mixture proportions and designations

Different types of air-entrained SCC mixtures were designed based on the optimum sand/aggregate (S/A) ratio of 0.50. The optimum S/A ratio was obtained based on the maximum bulk density of sand-coarse aggregate blends (Safiuddin 2008; Safiuddin *et al.* 2010a). The major design variables for the concrete mixtures were water/binder (W/B) ratio (0.30–0.50), RHA content (0–30%), and air content (4–8%). The mixture proportions (including HRWR dosages) and designations of the concretes are shown in Table 3. The concrete mixtures were designated based on the W/B ratio, RHA content, and design air content used. For example, the 'C30R0A6' designation was chosen for a concrete prepared with a W/B ratio of 0.30, 0% RHA content, and 6% design air content.

2.3. Mortar mixture proportions and designations

The mortars were formulated from their parent concretes. The proportions of fine aggregate (pit sand), cement, RHA, and water were determined based on the mixture proportions of the corresponding parent concretes. The mortars prepared separately had the same composition as the mortar phase of tested concretes. The dosages of HRWR were fixed at the saturation dosages. The saturation dosages of HRWR were obtained based on the flowing ability of the paste phase of mortar and concrete (Safiuddin 2008). The mixture proportions (including HRWR and AEA dosages) and designations of the mortars are given in Table 4. The mortars were designated based on the W/B ratio, RHA content, and design air content of the corresponding parent concretes. For instance, the 'M30R0A6' designation was selected for the mortar prepared with a W/B ratio of 0.30, 0% RHA content, and 6% design air content, as used in the corresponding parent concrete 'C30R0A6'.

2.4. Preparation and testing of mortars

The mortars were prepared using an epicyclic revolving type small mechanical mixer. The volume of the mortars produced was 3 liters. In preparing the mortars, the fine aggregate and binding material (cement alone or with RHA) were first dry-mixed for 1 min by a stainless spoon. After that, the mixing water including the initial dosage of AEA was added into the mixer bowl and a rest period of 30 s was allowed. Then the mixer was started, the HRWR dosage was gradually added, and the wet mixing was conducted for 3 min. Later, the subsequent AEA dosages were used to vary the air content of the mortars. For each incremental AEA dosage, further mixing was conducted for 2 min. The Chace indicator test

Table 3. Mixture proportions of various concretes (volume: 1 m^3)

Concrete type	W/B ratio	DAC (%)	CA (kg)	FA (kg)	C (kg)	RHA		W (kg)	HRWR dosage (% B)
						(% B)	(kg)		
C30R0A6	0.30	6	846.3	842.2	492.7	0	0	147.8	0.875
C30R15A6	0.30	6	829.9	825.8	418.8	15	73.9	147.8	1.75
C30R20A6	0.30	6	824.4	820.3	394.2	20	98.5	147.8	2.10
C35R0A6	0.35	6	876.1	871.8	422.3	0	0	147.8	0.70
C35R0A4	0.35	4	902.7	898.3	422.3	0	0	147.8	0.70
C35R0A8	0.35	8	849.4	845.2	422.3	0	0	147.8	0.70
C35R5A6	0.35	6	871.4	867.1	401.2	5	21.1	147.8	0.875
C35R10A6	0.35	6	866.7	862.4	380.1	10	42.2	147.8	1.05
C35R15A6	0.35	6	862.0	857.8	359.0	15	63.3	147.8	1.40
C35R15A4	0.35	4	888.6	884.2	359.0	15	63.3	147.8	1.40
C35R15A8	0.35	8	835.3	831.2	359.0	15	63.3	147.8	1.40
C35R20A6	0.35	6	857.3	853.1	337.8	20	84.5	147.8	1.75
C35R20A4	0.35	4	883.9	879.5	337.8	20	84.5	147.8	1.75
C35R20A8	0.35	8	830.6	826.5	337.8	20	84.5	147.8	1.75
C35R25A6	0.35	6	852.6	848.4	316.7	25	105.6	147.8	2.10
C35R30A6	0.35	6	847.9	843.7	295.6	30	126.7	147.8	2.45
C40R0A6	0.40	6	898.4	894.0	369.5	0	0	147.8	0.60
C40R15A6	0.40	6	886.0	881.7	314.1	15	55.4	147.8	1.00
C40R20A6	0.40	6	881.9	877.6	295.6	20	73.9	147.8	1.20
C50R0A6	0.50	6	928.3	923.7	296.8	0	0	148.4	0.50

Note: B = C + RHA; DAC = design air content

Table 4. Mixture proportions of various mortars (volume: 3 l)

Mortar type	Parent concrete	FA (kg)	C (kg)	RHA (kg)	W (kg)	HRWR dosage (% B)	AEA dosage (ml)
M30R0A6	C30R0A6	4.030	2.358	0	0.707	1.25	1.0–4.0
M30R15A6	C30R15A6	3.914	1.985	0.350	0.701	2.50	1.0–4.0
M30R20A6	C30R20A6	3.875	1.862	0.465	0.698	3.00	1.0–4.0
M35R0A6	C35R0A6	4.246	2.057	0	0.720	1.00	1.0–4.0
M35R0A4	C35R0A4	4.305	2.024	0	0.708	1.00	1.0–4.0
M35R0A8	C35R0A8	4.186	2.092	0	0.732	1.00	1.0–4.0
M35R5A6	C35R5A6	4.212	1.949	0.102	0.718	1.25	1.0–4.0
M35R10A6	C35R10A6	4.178	1.841	0.204	0.716	1.50	1.0–4.0
M35R15A6	C35R15A6	4.143	1.734	0.306	0.714	2.00	1.0–4.0
M35R15A4	C35R15A4	4.202	1.706	0.301	0.702	2.00	1.0–4.0
M35R15A8	C35R15A8	4.082	1.763	0.311	0.726	2.00	1.0–4.0
M35R20A6	C35R20A6	4.109	1.627	0.407	0.712	2.50	1.0–4.0
M35R20A4	C35R20A4	4.169	1.601	0.401	0.701	2.50	1.0–4.0
M35R20A8	C35R20A8	4.048	1.654	0.414	0.724	2.50	1.0–4.0
M35R25A6	C35R25A6	4.075	1.521	0.507	0.710	3.00	1.0–4.0
M35R30A6	C35R30A6	4.041	1.416	0.607	0.708	3.50	1.0–4.0
M40R0A6	C40R0A6	4.414	1.824	0	0.730	0.75	1.0–4.0
M40R15A6	C40R15A6	4.321	1.539	0.271	0.724	1.25	1.0–4.0
M40R20A6	C40R20A6	4.290	1.445	0.361	0.723	1.50	1.0–4.0
M50R0A6	C50R0A6	4.646	1.493	0	0.746	0.50	0.5–2.0

Note: B = C + RHA

(refer to Fig. 4) was carried out to determine the mortar air content immediately after the completion of mixing. The AASHTO T 199 (2008) standard procedure was followed except for filling the brass cup, where the mortar was placed without any rodding. The mortars were also tested for the flowing ability with respect to the flow spread using a standard flow mould. The details of this test are described in Safiuddin (2008) and Safiuddin *et al.* (2011).

2.5. Preparation and testing of fresh concretes

The fresh SCC mixtures were prepared using a revolving pan type mixer. The volume of the concretes produced was 25 liters. The dosages of HRWR were fixed based on the saturation dosages. The HRWR dosages used in most concretes were 70–80% of the saturation dosages. The dosages of AEA were decided based on the estimated AEA dosages obtained from the air content test results of the mortars. The AEA dosage was incorporated at the beginning whereas the HRWR dosage was added at the

Chace indicator used for determining the air content of mortars

Measurement of mortar air content

Fig. 4. Test setup and testing of mortars for air content

Type B air meter used for determining the air content of concretes

Measurement of concrete air content

Fig. 5. Test setup and testing of concretes for air content

later stage of mixing. The net mixing time for all concretes was 7 min. Immediately after the completion of mixing, the fresh concretes were tested for the air content. The ASTM C231-08 (2008) standard method was applied using a Type B air meter (refer to Fig. 5) with some exceptions for pouring and consolidation. The measuring bowl of the air meter was filled with the fresh concrete in one layer and without any consolidation. The fresh SCC mixtures were also tested for the flowing ability by a number of standard and non-standard tests to ensure that the concretes possessed sufficient self-consolidation capacity. The details of these tests are depicted in Safiuddin (2008) and Safiuddin *et al.* (2010a).

3. Test Results and Discussion

The mortars prepared were highly flowable. The flow spread of the mortars at HRWR saturation dosages varied in the range of 238–317 mm, which generally suggests an excellent flowing ability of SCC possessing a slump flow of 550–850 mm (Jin and Domone 2002; Safiuddin *et al.* 2010a; SCCEPG 2005). Indeed, the slump flow of various SCC mixtures produced in the present study differed in the range of 605–770 mm, as can be seen from Table 5. The other flow tests also exhibited the excellent flowing ability of SCC mixtures. The detailed test results for the flowing ability of mortars and concretes are reported in Safiuddin *et al.* (2010a, 2011). The present paper only emphasizes the air content results of various SCC mixtures and their mortar phases.

3.1. Air content of mortars

The results of the air content for different mortars are presented in Figs 6 to 9. The air content curves presented in Figs 6 to 8 are for the mortars formulated from the concretes with 6% design air content. In contrast, the air content curves shown in Fig. 9 are for the mortars formulated from the concretes with 4% and 8% design air contents. In general, the measured air content of the mortars varied from 3.7% to 19.4% for the AEA dosages used in the range of 0.5–4 ml. The air content of the mortars increased with increasing AEA dosages. This is mainly due to the formation of more air-voids from higher AEA dosage. Moreover, some additional air-voids leading to greater total air content can be produced from the previous AEA dosages with increased mixing time (Kosmatka *et al.* 2009; Safiuddin *et al.* 2006).

Table 5. AEA dosages and air content for various concrete mixtures

Concrete type	W/B ratio	RHA content (% B)	Slump flow (mm)	AEA dosage (% B)		Air content (%)	
				Estimated	Actual	Design	Actual
C30R0A6	0.30	0	710	0.030	0.026	6	5.7
C30R15A6	0.30	15	735	0.045	0.047	6	5.3
C30R20A6	0.30	20	770	0.052	0.056	6	5.7
C35R0A6	0.35	0	690	0.022	0.020	6	5.3
C35R0A4	0.35	0	700	0.015	0.016	4	4.3
C35R0A8	0.35	0	670	0.031	0.026	8	8.1
C35R5A6	0.35	5	700	0.026	0.025	6	5.5
C35R10A6	0.35	10	710	0.030	0.035	6	5.1
C35R15A6	0.35	15	720	0.043	0.045	6	5.1
C35R15A4	0.35	15	720	0.023	0.031	4	4.2
C35R15A8	0.35	15	720	0.072	0.072	8	8.0
C35R20A6	0.35	20	710	0.051	0.054	6	5.0
C35R20A4	0.35	20	690	0.027	0.036	4	4.3
C35R20A8	0.35	20	695	0.078	0.083	8	8.6
C35R25A6	0.35	25	740	0.060	0.070	6	5.6
C35R30A6	0.35	30	750	0.070	0.080	6	5.2
C40R0A6	0.40	0	665	0.013	0.011	6	6.1
C40R15A6	0.40	15	680	0.041	0.040	6	5.2
C40R20A6	0.40	20	675	0.049	0.051	6	5.3
C50R0A6	0.50	0	605	0.008	0.006	6	5.2

Note: B = C + RHA

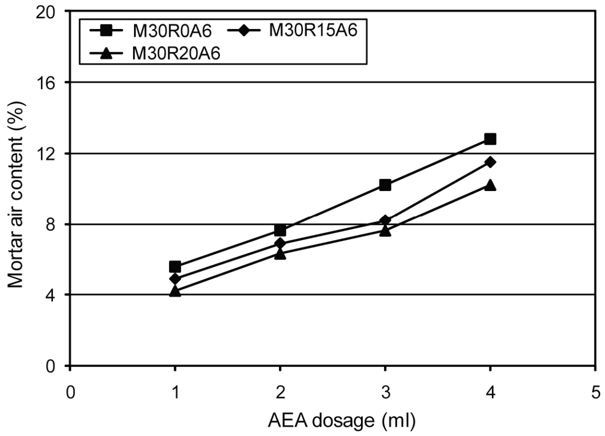

Fig. 6. Air content of various mortars (W/B = 0.30, concrete design air content = 6%)

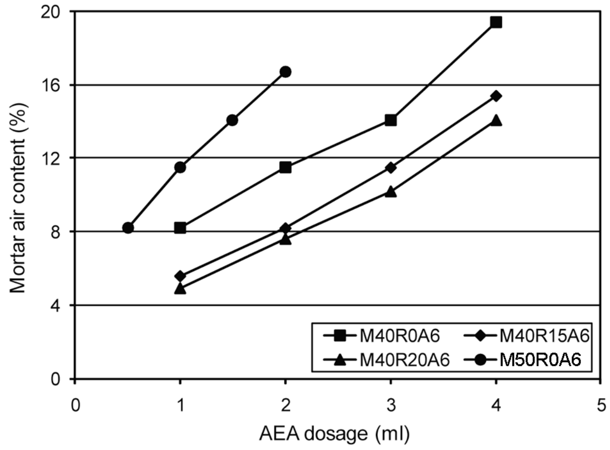

Fig. 8. Air content of various mortars (W/B = 0.40 and 0.50, concrete design air content = 6%)

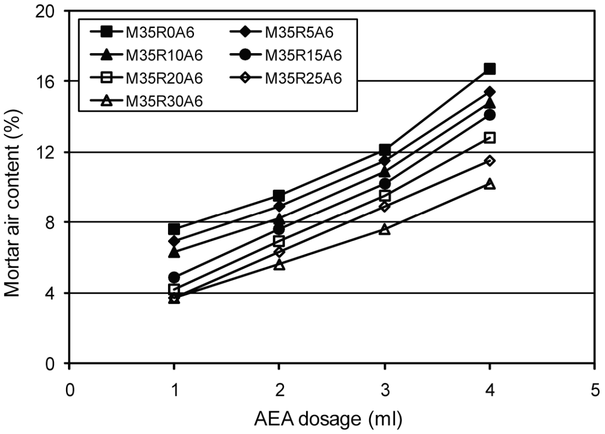

Fig. 7. Air content of various mortars (W/B = 0.35, concrete design air content = 6%)

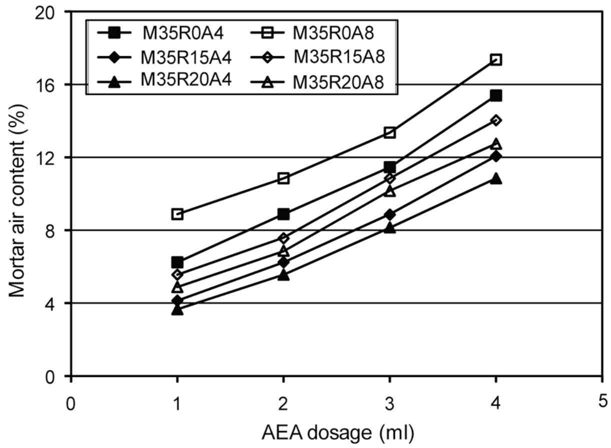

Fig. 9. Air content of various mortars (W/B = 0.35, concrete design air content = 4% and 8%)

The mortar air content curves shown in Figs 6 to 8 shifted to the downward direction with lower W/B ratio (higher binder content) and greater RHA content, indicating a decrease in air content. The effects of W/B ratio and RHA content on the air content of mortars are more evident from Figs 10 and 11, respectively.

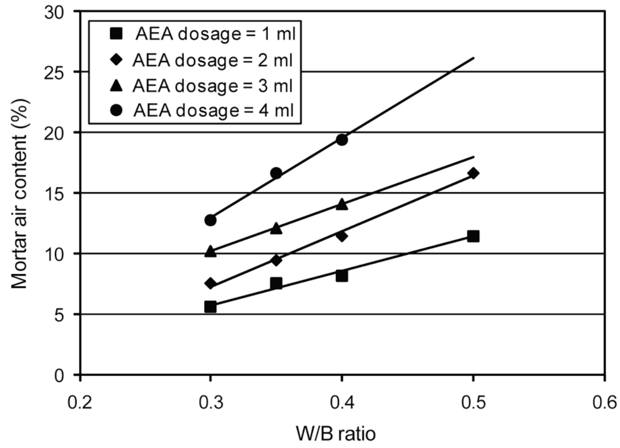

Fig. 10. Effect of W/B ratio on the air content of mortar

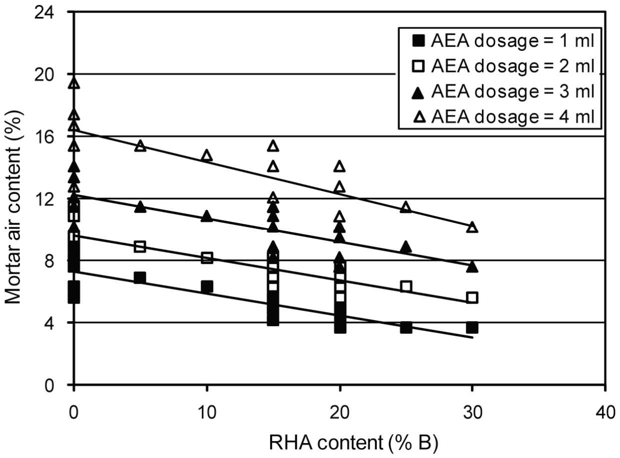

Fig. 11. Effect of RHA content on the air content of mortar

The binder content increased at a lower W/B ratio and resulted in a higher surface area. Also, the surface area of the binder significantly increased in the presence of RHA due to its porous honeycomb microstructure. The greater surface area decreased the available free water content in mortar. Consequently, the yield stress and plastic viscosity of mortar were increased. The increase in the yield stress was indicated by the flowing ability (flow spread) results of the mortars. The details of these results are given in Safiuddin *et al.* (2011). The flow spread is strongly correlated with the yield stress by an inverse linear relationship (Murata 1984; Safiuddin *et al.* 2010a; Schwartzentruber *et al.* 2006). The yield stress is a fundamental rheological property of cement-based materials as described in Bingham model (Chidiac and Habibbeigi 2005). Because of the inverse relationship, the higher the yield stress, the lower is the flow spread. Thus, a decrease in the flow spread reported in Safiuddin *et al.* (2011) was associated with an increase in the yield stress of mortar. Moreover, the estimated yield stress of concrete increased with lower W/B ratio and higher RHA content (Safiuddin *et al.* 2010a). The same effect (increase in yield stress) is also expected for mortar, since the rheological behaviors of mortar and concrete are similar (Banfill 1994). The increased yield stress suggests a loss of air-voids (Carlsward *et al.* 2003; Chidiac *et al.* 2003) from mortar, as the air-voids offset the forces of attraction between the solid particles in suspension. Furthermore, the increase in the plastic viscosity of mortar was denoted by the flowing ability (flow time) results of the paste phase of mortar or concrete. The details of these results are given in Safiuddin *et al.* (2010a). The flow time is strongly correlated with the plastic viscosity by a direct linear relationship (Safiuddin *et al.* 2010a; Schwartzentruber *et al.* 2006). The plastic viscosity is another fundamental rheological property of cement-based materials behaving as a Bingham fluid (Chidiac and Habibbeigi 2005). Owing to the direct relationship, the greater the plastic viscosity, the higher is the flow time. Thus, the increased flow times of the paste and concrete reported in Safiuddin *et al.* (2010a) indicated a greater plastic viscosity of mortar. The estimated plastic viscosity of concrete shown in Safiuddin *et al.* (2010a) also suggested that the mortar plastic viscosity increased with lower W/B ratio and higher RHA content. The increased plastic viscosity caused to decrease the air content of mortar. This is because the increased plastic viscosity tends to collapse some of the air-voids with higher internal pressure (Khayat and Assaad 2002). The collapsed air-voids can easily go out of the mortar at a high consistency maintained in the presence of HRWR. Besides, the increased RHA content required higher dosages of HRWR. The HRWR molecules impede the attachment of entrained air-voids onto the binding materials by reducing the attachment sites (Khayat and Assaad 2002). On the whole, the mortar air content decreased with lower W/B ratio and higher RHA content. This finding implies that the aeration problem of polycarboxylate-based HRWR was minimized in the present study. This is due to the combined effect of increased flowing ability, presence of RHA, and cement-admixture compatibility.

The mortar air content curves shown in Fig. 9 reveal that the air content of M35R0A4, M35R15A4 and M35R20A4 was lower than that of M35R0A8, M35R15A8 and M35R20A8, respectively, for given W/B ratio, RHA content, and AEA dosage. This is mostly due to the greater sand (fine aggregate) content of mortar. The sand content of M35R0A4, M35R15A4 and M35R20A4 was higher than that of M35R0A8, M35R15A8 and M35R20A8, as can be seen from Table 4. The higher sand content increases the yield stress and plastic viscosity of mortar due to confinement of some mixing water and enhanced interaction of sand particles, and thus destroys certain amount of the air-voids (Banfill 1994; Safiuddin 2008).

3.2. Estimated AEA dosages of concretes

The AEA dosages required to produce the target air content in concretes were estimated based on the air content results of the mortars. For this, the entrained concrete air content (design air content – entrapped air content) was converted into the equivalent mortar air content. Eq. (1) was used to determine the equivalent air content of the mortar phase (ASTM C231-08 2008):

$$A_{me} = \frac{100 A_c V_c}{100 V_m + A_c (V_c - V_m)}, \quad (1)$$

where: A_{me} – equivalent air content of mortar (%); A_c – entrained air content of concrete (%); V_c – air-free absolute volume of concrete (m^3); V_m – air-free absolute volume of the mortar phase of concrete (m^3).

The AEA dosages needed for the equivalent mortar air contents were calculated using the air content curves presented in Figs 6–9. These AEA dosages are applicable for the pure mortars, which were prepared separately instead of taking from the concrete mixtures. Hence, they were corrected by multiplying with the actual air-free volume fraction of the mortar present in concrete. Eq. (2) was applied to estimate the AEA dosages for the concretes. The estimated AEA dosages of different concretes are given in Table 5.

$$D_{ce} = \frac{D_{me} R_d}{1000 B} \times \phi_{mc} \times 100, \quad (2)$$

where: B – binder content of mortar (kg); D_{ce} – estimated AEA dosage for the specified air content of concrete (% B); D_{me} – dosage of AEA for the equivalent air content of mortar (ml); R_d – relative density of AEA; ϕ_{mc} – mortar volume fraction of concrete (m^3/m^3).

3.3. Actual AEA dosages and air contents of concretes

The actual AEA dosages used and the actual (measured) air content for various SCC mixtures are shown in Table 5. The actual air contents were within ±1.0% of the design air content. This variation is acceptable, as the maximum acceptable tolerance for air content measurement can be in the range of ±1.5% (ACI Committee 201 2008). However, the air content of SCC was prone to decrease with lower W/B ratio and higher RHA content. Also, the aeration effect of polycarboxylate-based HRWR was not pronounced in SCC mixtures, as understood based on the results of concrete air content test. Hence, the concrete with lower W/B ratio and higher RHA content needed a greater AEA dosage, as evident from Table 5. The reasons are the same as discussed in the case of mortar air content. In addition, the mortar volume influenced the air content of concrete. Depending on the W/B ratio and design air content, the increased mortar volume caused to decrease the air content of concrete due to the similar reasons as discussed in section 3.1. Therefore, more AEA dosage was required to achieve the target air content in concrete, as can be seen from Fig. 12.

3.4. Correlation of estimated and actual AEA dosages

The correlation between the actual and estimated AEA dosages of SCC was established. An excellent correlation (Fig. 13) between the estimated and actual AEA dosages was obtained for SCC despite its critical nature for air-void stability. The relationship was linear with a correlation coefficient of 0.967, as can be seen from Fig. 13. Some variations between the estimated and actual AEA dosages were detected possibly due to the differences in ambient environment, batch volume, mixture composition, mixing time, and type of mixer that occurred from mortar to concrete. However, the observed correlation suggests that the AEA dosage required for an air-entrained SCC can be determined based on the air content of its mortar phase. A similar correlation is also expected for the other types of concrete. This is because the concept of equivalent mortar air content can be applied to other concretes. Besides, achieving such correlation for a concrete other than SCC can be much easier due to the reduced risk of air-void instability.

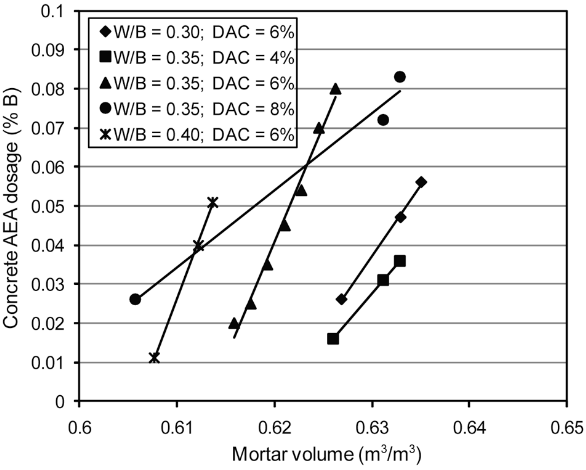

Fig. 12. Effect of mortar volume fraction on the AEA dosage of concrete (DAC: design air content)

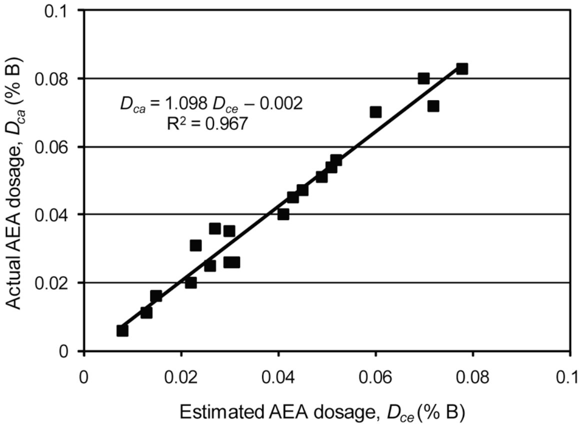

Fig. 13. Correlation between the estimated and actual AEA dosages for various concretes

4. Research Significance

The present study reports the air content results of various SCC mixtures and their mortar phases including RHA, and demonstrates a simple technique to estimate the AEA dosage for the target air content in concrete. The technique presented in this study will minimize the volume of experimental work to determine the AEA dosage for concrete. It will be cost-effective due to the minimum number of concrete trial mixtures, thus reducing the loss of materials and labor. In addition, the apparatus (Chace indicator) needed for this technique is less expensive than other air content measuring equipment such as air void analyzer (Baekmark *et al.* 1994; Lane 2006; Zhang and Wang 2005). The demonstrated test method is also very fast because of simplicity. The entire test can be conducted by less than 10 min. Also, the same mortar batch can be used with additional AEA dosage if needed. The quick and simple procedure can allow repeating the test without any significant loss of air-voids. This will accelerate the process of determining the AEA dosage for the target air content in concrete.

5. Conclusions

The following conclusions can be drawn from the results of the present study dealing with the air content of SCC and its mortar phase:

a. The air content of the mortars increased with the increase in AEA dosage due to the formation of more air-voids, and decreased with lower W/B ratio and higher RHA content because of the increases in binder content, binder surface area, and HRWR dosage.
b. The air content of the mortars for given W/B ratio, RHA content, and AEA dosage decreased with increased sand content due to the water confinement and greater interaction of sand particles.
c. The air content of the mortars facilitated to estimate the required AEA dosages for various SCC mixtures based on the concept of equivalent mortar air content.
d. The measured concrete air contents were within ±1.0% of the design concrete air contents. The AEA dosages for achieving a target concrete air content increased with lower W/B ratio and greater RHA content due to the increases in binder content and surface area, and HRWR dosage.
e. The estimated and actual AEA dosages for different SCC mixtures were strongly correlated. Hence, the AEA dosage needed for the target air content of SCC can be determined from the AEA dosage for the equivalent air content of its mortar phase.
f. The technique demonstrated for determining the AEA dosage of SCC can also be applied to the other types of concrete when the concept of equivalent mortar air content is valid.
g. The technique presented for deciding the AEA dosage of concrete is quick and simple. It is also cost-effective due to the minimum loss of materials and labor.

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ORO KIEKIS SAVITANKIAME BETONE IR JO SKIEDINIO DALYJE SU RYŽIŲ LUKŠTŲ PELENAIS

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Santrauka

Straipsnyje pateikiami oro kiekio nustatymo savitankiame betone (SCC) ir jo skiedinio dalyje su ryžių lukštų pelenais (RHA), naudojamais kaip papildoma cementavimo medžiaga, rezultatai. Be to, pateikiamas paprastas būdas parinkti orą įsiurbiančio priedo (AEA) dozę, siekiant gauti reikalingą oro kiekį SCC. Suprojektuoti skirtingi SCC mišiniai su skirtingu vandens ir rišiklio (W/B) 0,30–0,50 santykiu ir numatytu 4–8 proc. oro kiekiu, RHA buvo dedamas į betoną pakeičiant 0–30 proc. cemento pagal masę. Skiediniai buvo formuojami pagal jiems artimo betono sudėtis ir oro kiekis juose bandomas su skirtingomis AEA dozėmis. Nustatyta W/B santykio ir RHA kiekio įtaka oro kiekiui tiek skiedinyje, tiek betone bei skiedinio tūrio įtaka oro kiekiui betone. Be to, AEA dozės, reikalingos numatytam oro kiekiui betone pasiekti, nustatytos pagal ekvivalentinį oro kiekį skiedinyje. Vėliau SCC mišiniai su orą įsiurbiančiu priedu buvo pagaminti naudojant AEA ir išbandytas juose esantis oro kiekis. Tyrimų rezultatai rodo, kad tiek skiedinį, tiek betono oro kiekį labai veikia W/B santykis ir RHA kiekis. Oro kiekį betone taip pat smarkiai veikia skiedinio tūris. Mažėjant W/B santykiui, didėjant RHA kiekiui ir skiedinio tūriui AEA dozė turi būti didinama norimam oro kiekiui pasiekti. Taip pat faktinės AEA dozės atitiko suskaičiuotas betonų AEA dozes. Tarp faktinių ir suskaičiuotų AEA dozių gauta labai gera koreliacija. Ji rodo, kad AEA dozę, reikalingą numatytam oro kiekiui betone pasiekti, galima skaičiuoti pagal ekvivalentinį oro kiekį šio betono skiedinio dalyje.

Reikšminiai žodžiai: oro kiekis, orą įsiurbiantis priedas, betonas, mišinio sudėtis, skiedinys, ryžių lukštų pelenai.

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