AIR-VOID STABILITY IN FRESH SELF-CONSOLIDATING CONCRETES INCORPORATING RICE HUSK ASH

Md. Safiuddin, G.R. FitzGerald, J.S. West*[*] and K.A. Soudki
Department of Civil Engineering, University of Waterloo,
200 University Avenue West, Waterloo, Ontario, Canada N2L 3G1

Abstract

This paper presents the results of experimental study on air-void stability in fresh self-consolidating concretes. Two series of self-consolidating concrete were undertaken for conducting laboratory tests. Each series of concrete included three different fresh mixtures. The air-void stability in fresh concretes was investigated with respect to post-mixing and agitation. The air content of fresh concretes was determined at various test stages and adjusted considering aggregate correction factors. The flowing ability of the fresh concretes was also examined with regard to slump and slump flow. The entire testing period involved four stages extended to 60 and 90 minutes for series 1 and 2, respectively. Test results reveal that the slump and slump flow of the concrete mixtures were consistent in all test stages, and the loss of air content was minimal. The maximum loss of air content over the period of 60 and 90 minutes was less than 1.0%. Rice husk ash did not affect the air-void stability in fresh concretes. However, it increased the demand for high-range water reducer and air-entraining admixture. The overall test results indicate that the air-void stability in all fresh self-consolidating concretes was satisfactory.

Keywords: Air content, Air-void stability, Post-mixing, Rice husk ash, Self-consolidating concrete.

Introduction

Self-consolidating concrete (SCC) is a flowing concrete that spreads through congested reinforcement, fills every corner of the formwork and achieves consolidation under its own weight (Khayat 1999). In order to provide better durability performance and extended service life in freezing and thawing environments, SCC must contain an appropriate air-void system. For this, an adequate amount of entrained air-voids with proper specific surface and spacing factor should be retained in SCC. Usually, limits on volume of air-voids or air content are specified although the role of spacing factor is significant. This is because air content can be determined more easily and quickly than spacing factor. Canadian Standards Association (CSA) has specified various ranges of air content between 3 and 9% depending on maximum aggregate size and exposure conditions (CSA A23.1, 2004). These ranges of air content are recommended to create an adequate air-void system required for freeze-thaw and scaling resistance. However, when the specifications do not enforce any given air content but rather a spacing factor, an air content of 6% is usually suggested (Lessard et al. 1995). This air content generally maintains a spacing factor less than 230 μm if an effective air-entraining admixture is used in concrete mixture.

Air-voids are widely used for improving the freeze-thaw durability of concrete. The entrained air-voids improve the frost resistance of concrete in freeze-thaw environments, and thereby increase the service life of concrete structures (Cohen et al. 1992, Hayakawa et al. 1994, Siebel 1989). Although the mechanism of concrete deterioration due to freezing and thawing is still a subject of debate, the need for entrained air-voids has become indisputable. In general, the network of entrained air-voids offsets the dilating pressure posed by freezing water, and thus improves the performance of concrete

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[*] Corresponding author: e-mail. jswest@uwaterloo.ca

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in freezing and thawing environments (Neville 1996, Chatterji 2003). The dosage of air-entraining admixture is the most important parameter that controls the air-void system in concretes. A sufficient dosage of air-entraining admixture should be added to the fresh mixture to create the required volume of air-voids in hardened SCC. However, determining the correct dosage is not very straightforward. There are numerous factors such as mixture proportions, aggregate grading, cement composition, type of high-range water reducer, type and composition of supplementary cementing materials, quality of mixing water, mixing or placing methods, and temperature etc., that might affect air-entrainment, and therefore achieving the required air content in hardened concrete becomes much more difficult (ACI Committee 201, 2001; Du and Folliard 2005, Pigeon 1994). Nevertheless, the proper air-void system must be maintained in concrete to ensure a good resistance to freezing and thawing. Proper air-void system means that the entrained air-voids remain stable until the concrete is set, and becomes permanent in the hardened paste. This is particularly important for SCC, as the presence of high-range water reducer tends to destabilize the entrained air-bubbles during transport and placement of concrete (Saucier et al. 1990, Khayat and Assaad 2002). Many research reports indicate that high-range water reducers can cause some loss of air content during intermittent agitation (Jana et al. 2005, Johnston 1994). This is perhaps attributed to the production of greater large-size bubbles, which could easily disappear with time. Also, the large dosage of high-range water reducer could induce excessive fluidity and segregation, and thus may cause some loss of entrained air. Consequently, the air-void system in hardened concrete could be affected, and the freeze-thaw durability would be reduced.

Instable air-voids affect the air present in concrete, and thus air-void stability also influences other concrete properties such as strength and porosity. The air content of concrete is reduced due to the loss of instable air-voids. As a result, the total porosity of concrete is decreased and the concrete gains greater strength. In general, the average gain of compressive strength can be 3 to 5% for each percentage loss of air content (Neville 1996). However, the increase in compressive strength does not produce any significant benefit for air-entrained concrete since the desired level of compressive strength is already considered in mixture design. Instead, the loss of air content results in a significant reduction in freeze-thaw durability that cannot be overcome in any way. Therefore, the air-void stability in fresh SCC is significantly more important for freeze-thaw durability than strength.

Comprehensive studies have been conducted on air-void stability of low to medium slump concretes in presence of high-range water reducer (Baalbaki and Aïtcin 1994, Pigeon et al. 1989, Saucier et al. 1990). These studies report the effects of high-range water reducer, supplementary cementing materials, and cement-admixture compatibility on air-void stability in normal and high strength concretes with some contradictory results. In addition, Baekmark et al. (1994) investigated the air-void stability of medium-slump concretes with respect to post-mixing, re-dosing of high-range water reducer and pumping operation. They observed that the air-void stability in concrete is greatly affected by the type of air-entraining admixture. While conducting the air content test in all of the aforementioned studies, the concretes were consolidated by external means, which can affect the air-void system. External means of consolidation, including vibration, was found to produce a detrimental effect on quality of air-void system in air-entrained concrete (Stark 1986). Some air-voids can be lost during consolidation with rodding or vibration. Therefore, the air content obtained from an air-meter test may not represent the actual air content of the parent concrete mixture. This discrepancy is eliminated in SCC since it does not require any external means of consolidation. Still the air-void stability problem could occur in SCC due to other factors such as excessive fluidity and segregation, and destabilization caused by HRWR. Yet very few studies have been carried out to investigate the air-void stability in SCC.

Bouzoubaâ and Lachemi (2001), and Lachemi et al. (2003) developed air-entrained SCC and examined various fresh properties including air content. However, they did not study the air-void stability in SCC. Recently, Khayat (2000), and Khayat and Assaad (2002) investigated the air-void stability of SCC. They showed that the air-void stability could be ensured in SCC by a proper mixture composition including a suitable combination of chemical admixtures. An increase in the amount of fine material at a low water-binder ratio or the use of viscosity-modifying admixture can secure the appropriate air-void system during transport, placement and setting of SCC. However, none of the above studies investigated the effect of rice husk ash (RHA). The present study produced two series of SCC incorporating RHA and examined the air-void stability in fresh mixtures with respect to effects of post mixing and agitation. The effects were observed through subsequent determination of air content at different test stages.

Experimental Investigation

Experimental investigation was carried out through selection and testing of materials, determination of concrete mixture proportions, and preparation and testing of various fresh concretes.

Materials

Ordinary (ASTM Type I or CSA Type 10) portland cement, crushed granite stone, pit sand, non-crystalline amorphous rice husk ash (RHA), tap water, poly-carboxylic acid-based high-range water reducer (HRWR), and a synthetic air-entraining admixture (AEA) were used to produce various SCC. Crushed granite stone and pit sand were selected as coarse and fine aggregates, respectively, whereas rice husk ash was used as a supplementary cementing material. Prior to use in preparing concrete mixtures, the component materials were tested for a number of physical properties. These properties were useful to judge the suitability of the constituent materials. In addition, most of these properties were directly used in mixture proportioning of different concretes. The physical properties of the concrete materials are given in Table 1.

Table 1: Physical Properties of Constituent Materials

Material	Properties
Crushed granite stone	Maximum size: 19 mm Total evaporable moisture content: 0.1% Oven dry basis bulk density: 1670 kg/m^3 Void content: 37% Saturated surface-dry basis relative density: 2.71 Absorption: 1.5% Fineness modulus: 6.78
Pit sand	Maximum size: 4.75 mm Total evaporable moisture content: 0.1% Oven dry basis bulk density: 1860 kg/m^3 Void content: 28% Saturated surface-dry basis relative density: 2.62 Absorption: 1.0% Fineness modulus: 2.74
Ordinary portland cement	Relative density: 3.16 Blaine fineness: 412 m^2/kg
Rice husk ash (RHA)	Relative density: 2.07
Tap water	Density (24^{0}C): 997.28 kg/m^3
High-range water reducer (HRWR)	Relative density: 1.069 Solid content: 41%
Air-entraining admixture (AEA)	Relative density: 1.01 Solid content: 12.8%

Concrete Mixture Proportions

Two series of concretes, as shown in Table 2, were undertaken for testing of air-void stability. The fresh concrete mixtures were designed based on a weight-basis water-binder (W/B) ratio of 0.35, an air-dry and weight-basis sand-aggregate ratio of 0.50, and nominal air contents of 4 and 8%. For both air contents, the content of rice husk ash was varied with 0, 15 and 20% of binder by weight. The basic mixture proportions for the two series of concretes, as shown in Table 3, were determined based on the absolute volume of the constituent materials. The dosages of HRWR and AEA are not included in basic mixture proportions. HRWR and AEA were used in concrete as additives, and their dosages have been presented in Table 4. The amounts of HRWR shown in Table 4 are the saturation dosages for various concretes. These dosages were obtained by testing the flow of various binder pastes, which are not detailed here. Also, the proportions of coarse and fine aggregates given in Table 3 are based on their absolute volume in saturated surface-dry condition. But, the aggregates were batched in air-dry condition and hence they absorbed some mixing water. In addition, the liquid HRWR contributed some water during mixing. Therefore, the proportions of coarse and fine aggregates, and water presented in Table 3 were adjusted before concrete batching.

Table 2: Different Types of Self-consolidating Concrete for Testing of Air-void Stability

Concrete Series	Concrete Designation	W/B	Rice Husk Ash (% B)	Design Air Content (%)	Time of Testing (minute)
S1	C35/0/4	0.35	0	4	15, 30, 45, 60
	C35/15/4		15		
	C35/20/4		20		
S2	C35/0/8	0.35	0	8	15, 30, 60, 90
	C35/15/8		15		
	C35/20/8		20		

Table 3: Basic Mixture Proportions of Different Self-consolidating Concretes (W/B = 0.35)

Concrete Mixture	Coarse Aggregate kg/m^3	Fine Aggregate kg/m^3	Cement kg/m^3	Rice Husk Ash kg/m^3	Water kg/m^3
C35/0/4	902.7	898.3	422.3	0	147.8
C35/15/4	888.6	884.2	359.0	63.3	147.8
C35/20/4	883.9	879.5	337.8	84.5	147.8
C35/0/8	849.4	845.2	422.3	0	147.8
C35/15/8	835.3	831.2	359.0	63.3	147.8
C35/20/8	830.6	826.5	337.8	84.5	147.8

Preparation and Testing of Concretes

The fresh concretes were prepared using a pan-type mixer. Constituent materials were batched and mixed to produce the concretes. The total initial mixing time was 10 minutes. At first, fine and coarse aggregates were mixed for 1 minute with first quarter of the mixing water. Mixing of aggregate blend was continued for another 1 minute with the addition of AEA dispensed in second quarter of the mixing water. After 2-minute mixing, the mixer was stopped to add the binding material (cement alone or cement with RHA). Immediately, the mixer was restarted, third quarter of mixing water was added, and the mixing was continued for 2 additional minutes. Then the mixer was stopped again, the pan was covered with wet burlap and the aggregate-binder mixture was allowed for 3-minute rest. Thereafter, the mixer was restarted and the concrete materials were mixed for 3 more minutes with the gradual addition of HRWR dispensed in fourth quarter of mixing water. The saturation dosage of HRWR was used to produce the required flowing ability. For all concretes, the saturation dosage was split into four parts such as 70, 10, 10 and 10%, and added sequentially to maintain similar slump and slump flow over the whole testing period. The initial dosage of HRWR was equivalent to 70% of the saturation dosage. The remaining three parts of the saturation dosage were added to the concrete mixture at subsequent mixing stages, as shown in Table 2.

Table 4: Dosages of HRWR and AEA for Various Self-consolidating Concretes

Concrete Series	Concrete Designation	Saturation Dosage of HRWR		Dosage of AEA	
		(%B)	l/m^3	(%B)	ml/m^3
S1	C35/0/4	1.0	3.95	0.015	64.6
	C35/15/4	2.0	7.90	0.031	129.3
	C35/20/4	2.5	9.88	0.041	172.4
S2	C35/0/8	1.0	3.95	0.026	107.7
	C35/15/8	2.0	7.90	0.093	387.8
	C35/20/8	2.5	9.88	0.124	517.1

The air-void stability in fresh concretes was investigated with respect to post mixing and agitation. The entire testing task was comprised of four stages, as shown in Table 2. In both series of concrete, the primary mixtures were tested after 15 minutes from the start of mixing to determine the air content. Then the concrete mixtures were covered with wet burlap and allowed for rest followed by further mixing and testing. The rest period varied from 10 to 25 minutes depending on testing time shown in Table 2. The post-mixing was conducted for 2 minutes for each test stage. Similar flowing ability was maintained in fresh concretes during the entire test period. For this, an additional HRWR by 10% of the saturation dosage was added during post-mixing. The subsequent measurements for air content were taken after 30, 45 and 60 minutes for series 1. In case of series 2, these measurements were carried out after 30, 60 and 90 minutes. The air content of fresh concretes was determined in accordance with ASTM C231 (2004) with an exception that concrete sample was placed in the measuring bowl without any consolidation. The readings obtained from the air meter were corrected based on aggregate correction factors. The flowing ability of the fresh concretes was also examined during each test stage. For this, the slump and slump flow were determined using the Abram's slump cone specified in ASTM C143/C143M (2004). The freshly mixed concrete was placed in the slump cone in one layer and without any consolidation. Then the slump cone was raised vertically and the concrete was allowed to subside. The fall in height of initial concrete sample and the average diameter of the deformed concrete were measured and recorded as the slump and slump flow, respectively.

Test Results and Discussion

Various self-consolidating concretes were produced with desired flowing ability and air content. HRWR produced the self-consolidation effect, whereas AEA provided the desired air contents. The initial and successive dosages of HRWR worked very well to fulfil the performance criteria for flowing ability with respect to slump and slump flow. Also, consistent slump and slump flow were maintained during all test stages since the air-void stability could be affected by the flowing ability of the concretes. The ability of AEA to reduce the surface tension is generally decreased at lower flowing ability (Khayat and Assaad 2002). Thus, bigger and less stable air-voids could be produced. Also, more air-voids can be entrapped at lower flowing ability resulting in higher total air content. These drawbacks were eliminated in the present study, as the flowing ability of the concretes was almost the same at all test stages.

The measured slump and slump flow have been presented in Table 5 and Table 6, respectively. It can be seen from Table 5 that the slump was always consistent for each concrete. On the whole, the slump has varied from 270 to 280 mm, with an average of 275 mm and with a standard deviation of only about 2%. Moreover, Table 6 shows that the slump flow varied in the range of 670 to 720 mm. For each concrete, the slump flow was also consistent throughout the testing period. The average slump flow for all concretes was about 697 mm with a standard deviation of 11%. The slump of SCC usually varies from 250 to 280 mm (Ferraris et al. 2000). Again, the slump flow of SCC generally ranges between 600 and 800 mm (Khayat 2000, Xie et al. 2002). These criteria were maintained in the present study by split use of the saturation dosages of HRWR. For this, higher saturation dosages of HRWR were required in the presence of 15 and 20% RHA, as can be seen from Table 4. This is due to an increase in flocculation forces resulting from greater amount of fine particles and higher specific surface area. Therefore, the demand for HRWR was increased to improve the dispersion of the binding materials.

Table 5: Variation of Slump with Time for Different Self-consolidating Concretes

Concrete Series	**Concrete Designation**	**Slump (mm)**			
		T = 15 min.	T = 30 min.	T = 45 min.	T = 60 min.
S1	C35/0/4	275	275	275	270
	C35/15/4	280	275	275	275
	C35/20/4	275	275	275	275
		T = 15 min.	T = 30 min.	T = 60 min.	T = 90 min.
S2	C35/0/8	275	275	275	275
	C35/15/8	280	275	275	275
	C35/20/8	275	275	275	270

Table 6: Variation of Slump Flow with Time for Different Self-consolidating Concretes

Concrete Series	**Concrete Designation**	**Slump Flow (mm)**			
		T = 15 min.	T = 30 min.	T = 45 min.	T = 60 min.
S1	C35/0/4	700	700	700	680
	C35/15/4	720	705	700	700
	C35/20/4	690	695	700	695
		T = 15 min.	T = 30 min.	T = 60 min.	T = 90 min.
S2	C35/0/8	670	680	700	695
	C35/15/8	720	700	710	695
	C35/20/8	695	690	695	690

The results for air content of various SCC have been presented in Figures 1 and 2. It can be seen from Figure 1 that the air content varied from 3.5 to 4.3% for concretes under series 1. Conversely, the air content ranged from 7.5 to 8.6% for concretes under series 2, as can be seen from Figure 2. Hence, the actual air contents deviated from the design air contents (4 and 8%) within the range of ±0.6%. This is below the acceptable tolerance for air content measurement of ±1.5% (ACI Committee 201, 2001). In a few cases, the air content observed during second stage of testing at 30 minutes from concrete batching was slightly higher than the initial air content. This is possibly due to enhanced dispersion of the entrained air under more mixing action. The overall test results indicate that the air-void stability in all fresh self-consolidating concretes was good. The maximum loss of air content over the period of 60 and 90 minutes was less than 1.0% for all concretes. This is below the generally occurring air loss of 1 to 2% due to transportation of concrete (Kosmatka et al. 2002). Also, there was no significant difference in loss of air content between series 1 and 2 due to post-mixing and agitation. It suggests that the concrete placement can be delayed up to 60 to 90 minutes from the time of batching, while maintaining the desirable air content. This time length is adequate for the transport of concrete from ready-mixed plant to the construction site.

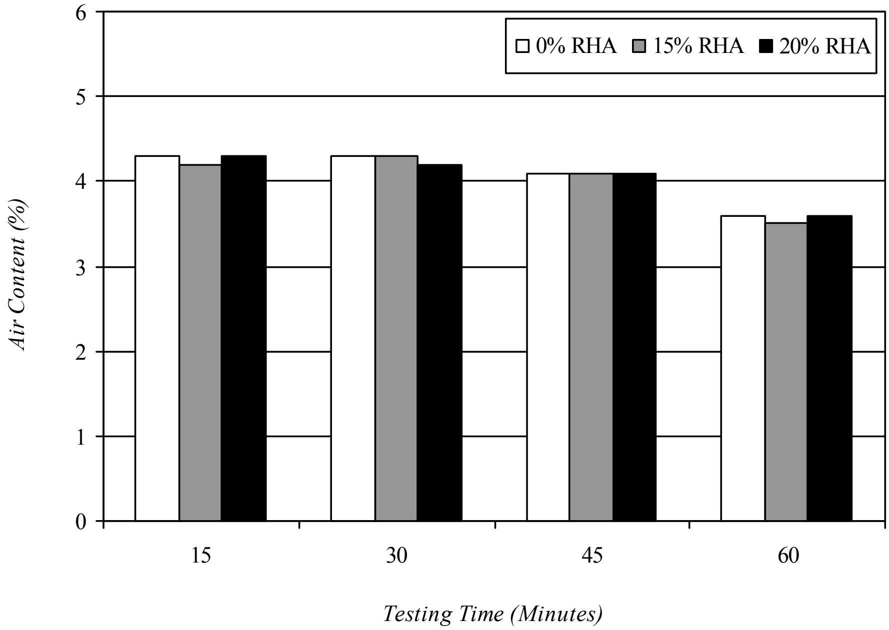

Figure 1: Variation of Air Content with Time for Self-consolidating Concretes under Series 1

The air-void stability observed in various fresh SCC is attributed to the relatively high binder content, low water-binder ratio and high sand-aggregate ratio. These properties are not only conducive to the flowing ability of concretes, but also enhance air-void stability (Khayat and Assaad 2002). In the present study, the concretes were prepared using a relatively low coarse aggregate content with a higher amount of binder. In addition, the saturation dosages of HRWR dispersed the binding materials and maintained good fluidity in the concrete mixtures. As a result, the inter-particle friction and collision of aggregates were reduced during mixing, handling and placement, which might produce more stable air-voids in fresh concrete. Moreover, the split addition of HRWR did not affect the air content of fresh concrete. Schemmel et al. (1994) observed similar results in case of high-performance concrete. However, it might have some effects on air-void system in hardened concrete. Higher dosages of HRWR can drive some of the entrained air-voids to coalesce resulting in increased spacing factor for a given air content (Pigeon et al. 1989, Siebel 1989). Nevertheless, this issue is beyond the scope of the present study.

The air-void stability in fresh concretes was not affected by RHA. This is evident from Figures 1 and 2. However, the presence of RHA increased the demand for AEA for a given range of air content. It can be seen from Table 4 that greater AEA dosages were required for concretes with 15 and 20% RHA in both series. This is mostly due to increased paste viscosity and reduced attachment of entrained air-voids. The paste viscosity was increased due to fine particle size and extremely high specific surface area of RHA. The increased paste viscosity increases the internal pressure in air-voids that causes collapse of some entrained air-voids (Khayat and Assaad 2002). Consequently, a reduction in fresh air content occurs and more AEA is required to compensate for this loss. Some AEA molecules could also be adsorbed or absorbed in porous and honeycombing microstructure of RHA. Thus, a lower amount of AEA will be available for air-void formation and stabilisation. Furthermore, HRWR can impede the attachment of entrained air-voids onto binding materials by reducing the attachment sites (Khayat and Assaad 2002). Some HRWR, particularly poly-carboxylic acid-based HRWR, also produce a steric repulsion with long grafted side chains (Mindess et al. 2003) that may further reduce the attachment of air-voids on cement and RHA particles. Hence, some air-voids could become less stable and combine to seep out of the concrete mixture, resulting in a higher demand for AEA. Both attachment site reduction and steric repulsion effects of HRWR could be more pronounced in case of 15 and 20% RHA, as greater dosages were used to obtain the desired flowing ability of concretes.

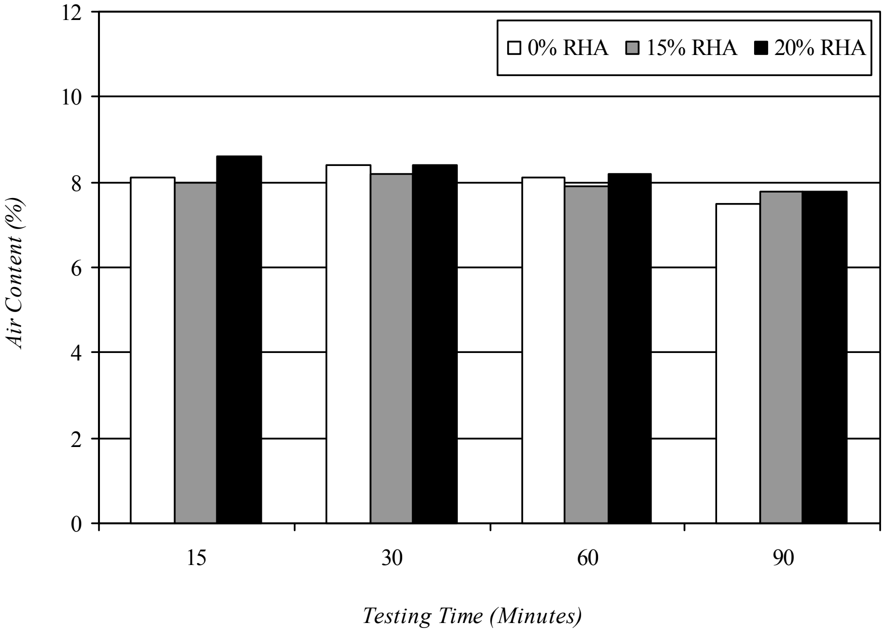

Figure 2: Variation of Air Content with Time for Self-consolidating Concretes under Series 2

Conclusions

1. Air-void stability in various fresh self-consolidating concretes was not affected by post-mixing and agitation, as the air content at various test stages did not differ significantly.
2. Air-void stability in various fresh self-consolidating concretes was good over the period of 60 to 90 minutes, as the maximum loss of air content remained below 1%.
3. Rice husk ash increased the demand for air-entraining admixture for a given air content but it did not affect the overall air-void stability in fresh self-consolidating concretes.
4. The flowing ability of various self-consolidating concretes had no effect on air-void stability, as the slump and slump flow of the concretes were kept consistent in all test stages.
5. The split addition of the saturation dosage of HRWR maintained consistent flowing ability at all test stages but it did not affect the air-void stability in fresh self-consolidating concretes.

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