Evaluation of hardened properties of self-consolidating high performance concrete using supplementary cementing material

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***Abstract*— This paper mainly presents the hardened properties of self-consolidating high performance concrete (SCHPC). A variety of SCHPCs were produced with different water/binder (W/B) ratios, rice husk ash (RHA) contents, and also air contents. The required filling ability and air content were achieved in all freshly mixed SCHPCs. The hardened self consolidating high performance concretes were tested for compressive strength and ultrasonic pulse velocity. The effects of Water/Binder ratio, Rice Husk Ash content, and air content on these hardened properties were observed. Test results revealed that the compressive strength and ultrasonic pulse velocity increased with lower W/B ratio and higher RHA content. It was witnessed that the air content decreased the compressive strength and ultrasonic pulse velocity.**

***Index Terms*— Air content, Concrete, Hardened properties, Rice husk ash, Water/binder ratio**

I. Introduction

Advancements in concrete technology have resulted in the development of a new type of concrete, which is known as self- consolidating high performance concrete (SCHPC). The merits of SCHPC are based on the concept of self-consolidating and high performance concretes. Self-consolidating concrete (SCC) is a highly flowing concrete that spreads through congested reinforcement, reaches every corner of the formwork, and is consolidated under its own weight without vibration or any other means of consolidation [1]. SCC must require excellent filling ability, good passing ability, and adequate segregation resistance. However, it does not include high strength and good durability as the essential performance criteria. Conversely, high performance concrete (HPC) has been defined as a concrete that is properly designed, mixed, placed, consolidated, and cured to provide high strength and low transport properties or good durability [2]. HPC generally exhibits a good segregation resistance. But it does not provide excellent filling ability and good passing ability like SCC, and therefore needs an external means such as rodding or vibration for proper consolidation. When the performance criteria for high strength and low transport properties or good durability of HPC are included in SCC with a lower water/binder (W/B) ratio, it can be referred to as SCHPC. Hence, an SCHPC is a special concrete, which offers excellent filling ability and passing ability, adequate segregation resistance, high strength, and good durability. The performance criteria, which should be satisfied for the major fresh and hardened properties of SCHPC are given in Table 1.

SCHPC is produced by utilizing the benefits of high-range water reducer (HRWR) and supplementary cementing material (SCM). The use of HRWR is essential to produce SCHPC. A HRWR contributes to achieve excellent filling ability and passing ability in fresh SCHPC. The hardened properties of SCHPC are also improved in the presence of HRWR due to the enhanced dispersion of binder particles and improved paste densification. Along with HRWR, SCMs are generally incorporated in SCHPC to enhance the strength and durability, and to reduce the cement content of concrete. Several well-known SCMs such as silica fume, ground granulated blast-furnace slag, and fly ash have been used to produce SCHPC [9,15–17]. However, the expense of several common SCMs such as silica fume and high reactivity metakaolin increases the overall material cost of SCHPC. In particular, the use of silica fume may be cost-prohibitive in developing countries. Therefore, it is necessary to use an alternative less expensive SCM such as rice husk ash (RHA) to produce cost-effective SCHPC.

RHA is typically obtained by the controlled burning of rice husks at 500–800 °C (conventional thermal treatment) [18]. The quality of RHA can be improved by pre-treating the rice husks with an acid leaching and then burning them under controlled conditions (chemical–thermal treatment) [19]. If processed and used properly, RHA offers similar benefits like silica fume with regard to the improved hardened properties and durability of concrete [19–23].

Table 1
Performance criteria for the key fresh and hardened properties of SCHPC

Test method	Property	Criterion
SCC property		
Slump flow (SF)	Filling ability (flow spread)	550–850 mm [3]
V-funnel flow	Filling ability (flow time)	6–12s [4]
Orimet flow	Filling ability (flow time)	2.5–9s [5]
Fill-box flow	Passing ability (filling percentage)	90–100% [4]
L-box flow	Passing ability (blocking ratio)	0.8–1.0 [4]

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U-box flow	Passing ability (filling height)	630 mm [4]
J-ring flow (JF)	Passing ability (blocking)	(SF–JF)650 mm [6]
Penetration depth	Segregation resistance	68 mm [7]
Sieve segregation	Segregation resistance	618% [8]
HPC property		
Air content by pressure method	Fresh air content	4–8% [9]
Compression using cylinders	Early-age compressive strengths	>20 MPa [10]
	28 and 91 days compressive strengths	>40 MPa [10]
Ultrasonic pulse velocity by a PUNDITa	Physical quality or condition	P4575 m/s [11]
Porosity by fluid displacement method	Total porosity as an indicator of strength and durability	7–15% [12]
Absorption by water saturation technique	Water absorption as an indicator of durability	3–6% [13]
True electrical resistivity by Wenner probe	Electrical resistance to corrosion	>(5–10) kX cm [14]
Rapid chloride ion penetration	Electrical charged passed as an indicator of corrosion resistance	<2000 C [10]
Normal chloride ion penetration at 6 months	Penetrated chloride value as an indicator of corrosion resistance	<0.07% [10]
Resistance to freezing and thawing	Durability factor after 300 cycles of freeze–thaw	>0.80 [2]

[a] Portable ultrasonic non-destructive digital indicating tester.

In addition, the usage of RHA minimizes the environmental burden associated with the waste disposal problem caused by the rice milling industry. The recent yearly production of rice in the world is approximately 560 million metric tons [24]. Rice husk constitutes about one fifth of the dried rice [25]. Therefore, nearly 112 million metric tons of rice husks are generated every year. This is causing a large environmental load, which can be reduced if RHA is used in concrete production. Moreover, the use of RHA decreases the demand for cement in the construction industry, and thus reduces the cost of concrete production and lessens the environmental pollution caused by the CO_2 emission from the cement factories. Hence, RHA not only improves the concrete properties and durability, but also provides economic and environmental benefits. Realizing the manifold benefits of RHA, it has been used successfully to produce high strength and high performance concretes [20,21]. Yet, the use of RHA in SCHPC is very limited. No comprehensive research has been conducted to explore the potential of RHA for SCHPC by investigating its effects on the hardened properties and durability of this concrete.

The present study produced a number of SCHPCs utilizing conventional RHA as an SCM. The target slump flow (a measure of filling ability) and air content were maintained in the fresh concretes using adequate dosages of HRWR and air-entraining admixture (AEA), respectively. The effects of RHA were mainly investigated with respect to the key hardened properties of concrete. The effects of W/B ratio and air content on the hardened properties were also observed. Both destructive and non-destructive tests were performed to determine the hardened properties of the concretes. The hardened properties obtained were compressive strength and ultrasonic pulse velocity.

II. EXPERIMENTAL PROGRAM

2.1 Constituent materials

Coarse aggregate (CA), fine aggregate (FA), normal portland cement (C), amorphous RHA, normal tap water (W), a polycarboxylate based HRWR, and a synthetic AEA were used to produce various SCHPCs adopted in the present study.

The coarse aggregates (CA) with a maximum size of 19 mm were used in concrete. The concrete sand was locally available natural pit sand with a maximum size of 4.75 mm. It was used as the fine aggregate (FA) for concretes. Normal portland cement was used as the main cementing material for various SCHPCs. RHA was used as an SCM for different SCHPCs. It was originally collected from Vellore, Tamil Nadu, India. It was available in very fine powder form with angular particle size and grey color. The surface fineness of RHA was much higher than that of cement due to the cellular particles with honeycomb microstructure.

2.2. Mixture proportions

The concrete mixtures were designed based on the W/B ratios of 0.30, 0.35, 0.40 and 0.50, and using RHA substituting 0% to 30% of cement by weight. Cement and RHA acted as the total binder (B) for the concretes. In addition, the optimum Sand/Aggregate (S/A) ratio of 0.50 leading to a maximum bulk density (minimum void content) in aggregate blend was used for all concrete mixtures. A total air content (AC) of 6% was adopted to design the air-entrained SCHPCs whereas 2% entrapped air content was considered in designing the non air-entrained SCHPC. The concrete mixtures were designed to obtain a slump flow (SF) in the range of 600–800 mm, which gives excellent filling ability. The dosages of HRWR were decided to attain the required slump flow. The HRWR dosages used for different SCHPCs were 70–80% of the saturation dosages. The saturation dosages of HRWR were determined by testing the filling ability of the binder paste components of various SCHPCs. In addition, the AEA dosages were fixed to achieve a total air content of 6 ± 1.5% in air-entrained SCHPCs.

The mixture proportions and designations of various SCHPCs are given in Table 2. The concretes were designated based on the W/B ratio, RHA content, and design air content. For example, the ‘C40R15A6’ designation was used for the concrete prepared with a W/B ratio of 0.40, 15% RHA content, and 6% design air content.

2.3. Preparation of fresh concretes and hardened test specimens

The concrete constituent materials were batched for mixing based on the mixture proportions shown in Table 2. The batch volume of the fresh concretes was taken 15% more than the required to compensate the loss during mixing and testing. The component materials were mixed in a revolving pan type mixer to produce the fresh SCHPCs. The AEA dosage was added at the beginning whereas the HRWR dosage was used at the later stage of mixing. The net mixing time for all concrete mixtures was 7 min. The hardened test specimens were prepared from the fresh concretes through several steps such as moulding, demoulding, and curing. The cylinder specimens of Ø 100 x 200 mm size were moulded in moulds. The fresh concrete was poured into the cylinder moulds in one layer, and no vibration or rodding was used for consolidation. Immediately after casting, the cylinder specimens were left undisturbed at room temperature. The specimens were demoulded, marked, and transferred to curing at the age of 24 hrs. The curing was carried out until the day of testing.

2.4 Test procedures

The compressive strength and ultrasonic pulse velocity were determined using Ø 100 x 200 mm cylinders at each testing age. The compression test was carried out at the ages of 3, 7, 28, and 56 days in accordance.

The ultrasonic pulse velocity of the concretes was determined at the ages of 28 and 56 days according. A portable ultrasonic non-destructive digital indicating tester (PUNDIT) was used to determine the transit time of ultrasonic pulse through concrete specimens. The specimens were air-dried at room temperature for 24 hrs prior to the testing of ultrasonic pulse velocity.

Table 2
Details of the concrete mixture proportions

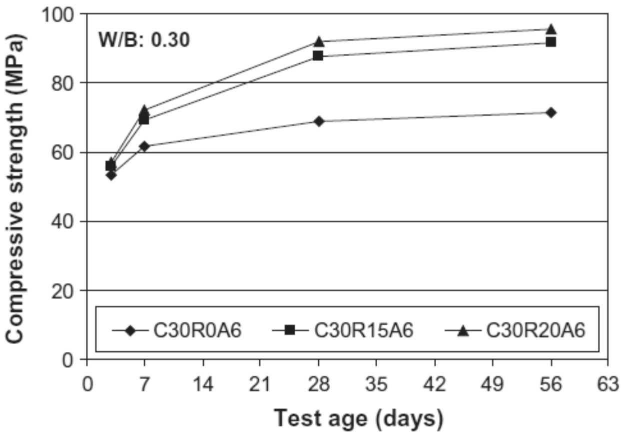
Concrete type	Basic proportions (kg/m^3) CA	FA	C	RHA	W	Admixture dosages (% B) HRWR	AEA	SF[a] (mm)	AC[b] (%)
C30R0A6	846.3	842.2	492.7	0	147.8	0.875	0.026	710	5.7
C30R15A6	829.9	825.8	418.8	73.9	147.8	1.75	0.047	735	5.3
C30R20A6	824.4	820.3	394.2	98.5	147.8	2.10	0.056	770	5.7
C35R0A6	876.1	871.8	422.3	0	147.8	0.70	0.020	690	5.3
C35R5A6	871.4	867.1	401.2	21.1	147.8	0.875	0.025	700	5.5
C35R10A6	866.7	862.4	380.1	42.2	147.8	1.05	0.035	710	5.1
C35R15A6	862.0	857.8	359.0	63.3	147.8	1.40	0.045	720	5.1
C35R20A6	857.3	853.1	337.8	84.5	147.8	1.75	0.054	710	5.0
C35R25A6	852.6	848.4	316.7	105.6	147.8	2.10	0.070	740	5.6
C35R30A6	847.9	843.7	295.6	126.7	147.8	2.45	0.080	750	5.2
C40R0A6	898.4	894.0	369.5	0	147.8	0.60	0.011	665	6.1
C40R15A6	886.0	881.7	314.1	55.4	147.8	1.00	0.040	680	5.2
C40R20A6	881.9	877.6	295.6	73.9	147.8	1.20	0.051	675	5.3
C50R0A6	928.3	923.7	296.8	0	148.4	0.50	0.006	605	5.2
C50R0A2	940.1	935.5	334.8	0	167.4	0.50	0	600	1.8

[a] Slump flow.
[b] Air content.

III. Results and Discussion

3.1 Compressive strength

The average compressive strengths of the concretes are presented in Fig. 1. The gain in compressive strength continued to occur over the 56 days curing period. The 28-days compressive strength varied from 42.7 to 94.1 MPa while the 56-days compressive strength differed from 44.9 to 98.4 MPa for different concretes. The highest level of later-age compressive strength was achieved for C35R30A6, which contained 30% RHA at the W/B ratio of 0.35. Conversely, the lowest level of compressive strength at all ages was obtained for C50R0A6, which was produced with a W/B ratio of 0.50 and without any RHA. Nevertheless, the performance criteria for both early-age and later-age compressive strengths of SCHPC, as mentioned in Table 1 were fulfilled for all concretes. The compressive strength of the concretes with and without RHA increased with a lower W/B ratio, as obvious from Fig. 2. The increase in compressive strength is directly related to the reduction in concrete porosity [28]. In the current study, the total porosity of concrete decreased with a lower W/B ratio. The micro- structure of concrete is improved in both bulk paste matrix and interfacial transition zone with a reduced porosity [29]. Also, the cement content became higher at a lower W/B ratio since the water content was kept constant for all concretes, as evident from Table 2. The increased cement content improves the physical packing of aggregates and produces a greater amount of calcium silicate hydrate (C–S–H) leading to a higher compressive strength.



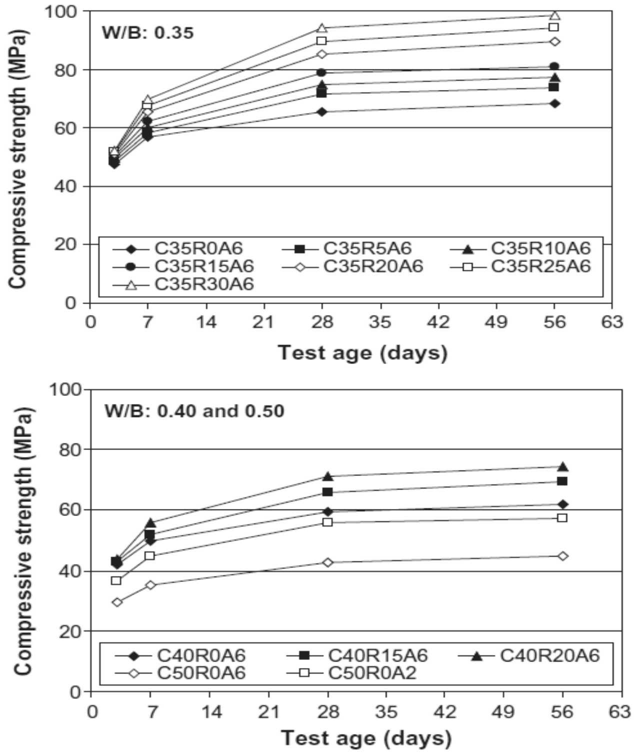


Fig. 1. Compressive strength development of various concretes

The RHA increased the compressive strength of concretes at the ages of 7, 28 and 56 days, as evident from Figs. 1 and 2. The improvement of compressive strength is mostly due to the microfilling ability and pozzolanic activity of RHA [30,31]. With a smaller particle size, the RHA can fill the microvoids within the cement particles. Also, the RHA is a highly reactive SCM. It readily reacts with water and calcium hydroxide (a by-product of cement hydration) and produces additional C–S–H [31]. The additional C–S–H reduces the porosity of concrete by filling the capillary pores, and thus improves the microstructure of concrete in bulk paste matrix and transition zone leading to an increased compressive strength.

The increased air content decreased the compressive strength of concrete. This is obvious from the compressive strength results of the concretes 'C50R0A2' and 'C50R0A6', as presented in Fig. 1. The reduction in compressive strength was about 4 MPa per 1% increase in air content. This is due to the entrained air-voids that increase the total void content of concrete [28]. The increased void content decreases the load carrying capacity of concrete, and thus produces a lower compressive strength.

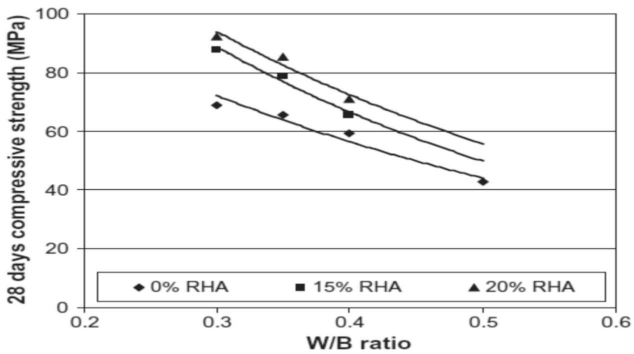


Fig. 2. Effects of W/B ratio and RHA content on the compressive strength of concrete.

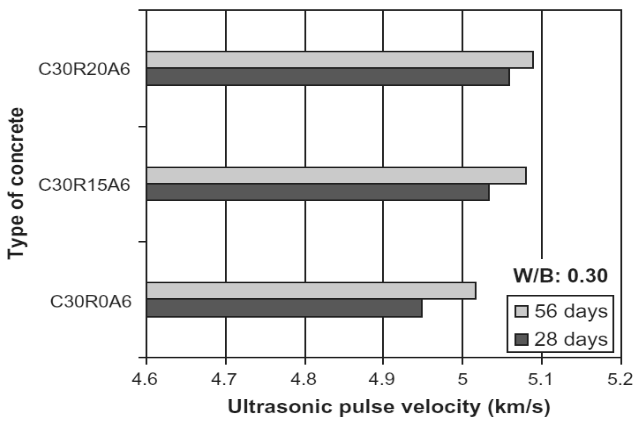
3.2. Ultrasonic pulse velocity

The average test results for the 28 and 56 days ultrasonic pulse velocity of the concretes are presented in Fig. 3. The ultrasonic pulse velocity varied in the range of 4.730–5.097 km/s, thus indicating an excellent physical condition of the concretes. This is because an ultrasonic pulse velocity higher than 4.575 km/s generally represents the excellent quality of concrete [11]. The excellent ultrasonic pulse velocity was attained mostly due to the improved pore structure of concretes with reduced porosity and small pore sizes.

The ultrasonic pulse velocity of the concretes with and without RHA increased with a lower W/B ratio, as evident from Fig. 4. The highest level of ultrasonic pulse velocity was achieved for the concretes prepared with the W/B ratio of 0.30. In contrast, the lowest level of ultrasonic pulse velocity was obtained for the concretes produced with the W/B ratio of 0.50. The improvement in ultrasonic pulse velocity at a lower W/B ratio was due to the reduced porosity of concrete resulting from a greater volume of hydration products.

The presence of RHA increased the ultrasonic pulse velocity of the concretes, as can be seen from Figs. 3 and 4. The physical and chemical modifications of the pore structure of concrete occur in the presence of RHA due to its microfilling and pozzolanic effects as discussed in Section 3.1. This results in the pore refinement and porosity reduction leading to a dense pore structure in both bulk paste matrix and transition zone of concrete that contributes to a higher ultrasonic pulse velocity. However, the increase in ultrasonic pulse velocity was not as significant as the increase in compressive strength due to the reduced aggregate content. The aggregate content decreased with the increase in RHA content, as can be seen from Table 2. This can diminish the positive effect of RHA on the ultrasonic pulse velocity of concrete, since a reduction in aggregate content decreases the ultrasonic pulse velocity of concrete [11,32].

The ultrasonic pulse velocity of concrete was affected by the entrained air-voids of concrete. It can be seen from Fig. 3 that the ultrasonic pulse velocity of the non-air-entrained concrete (C50R0A2) was higher than that of air-entrained concrete (C50R0A6) produced with the same W/B ratio. This is due to the greater number of pores and C–S–H gel/pore interfaces in the presence of entrained air-voids that may delay the propagation of the ultrasonic pulse, thus reducing its velocity through concrete.



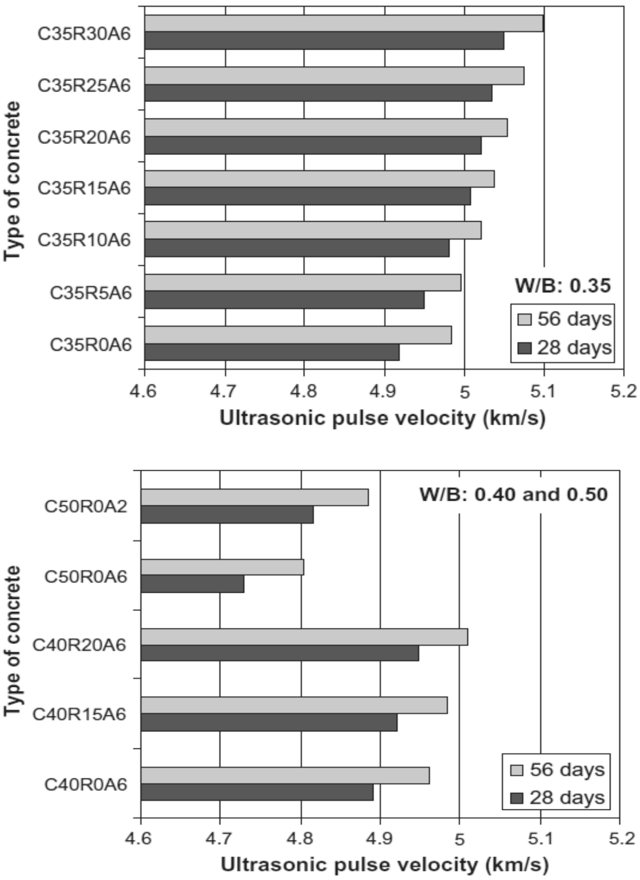


Fig. 3. Ultrasonic pulse velocity of various concretes

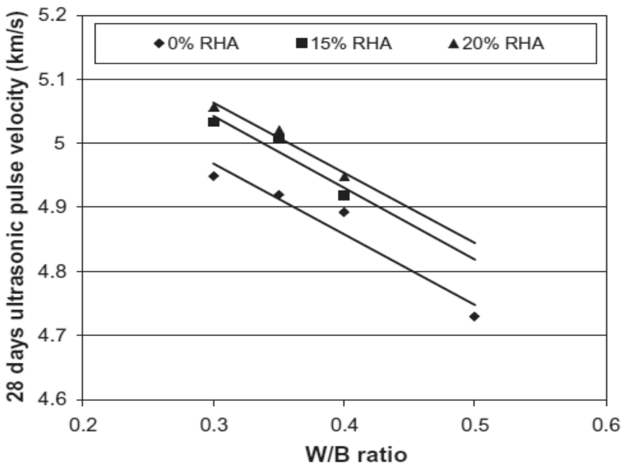


Fig. 4. Effects of W/B ratio and RHA content on the ultrasonic pulse velocity of concrete

IV. Conclusions

Based on the experimental results for various SCHPCs produced in the present study, the following conclusions can be drawn:

a. The hardened properties of the concretes were enhanced with lower W/B ratio due to the improved paste densification resulting from a greater amount of hydration products in the presence of higher binder content.

b. The hardened properties of the concretes were progressively improved with the increased content of RHA because of its microfilling and pozzolanic effects, which improve the microstructure and pore structure of concrete in bulk paste matrix and transition zone.

c. The compressive strength and ultrasonic pulse velocity of the concretes increased with lower W/B ratio and higher RHA content.

d. The excellent hardened properties were achieved at 15% RHA, which was also suitable to provide the required slump flow and air content with relatively low dosages of HRWR and AEA, respectively. In addition, no mixing and handling difficulties were experienced for the SCHPCs including the RHA content of 15%. Hence, 15% RHA was the optimum RHA content for SCHPC.

e. The increased air content decreased the compressive strength since the air-voids increased the total void content, which reduced the load carrying capacity of concrete. Also, the increase in air content decreased the ultrasonic pulse velocity of concrete, as the increased amount of air-voids delayed the propagation of ultrasonic pulse.

References

[1] Khayat KH. Workability, testing, and performance of self-consolidating concrete. ACI Mater J 1999;96(3):346–53.
[2] Russell HG. ACI defines high-performance concrete. Concr Int 1999;21(2):56–7.
[3] SCCEPG. The European guidelines for self-compacting concrete: specification, production and use. West Midlands, UK: Self-Compacting Concrete European Project Group (SCCEPG), The European Federation of Concrete Admixtures Associations; 2005.
[4] EFNARC. Specifications and guidelines for self-consolidating concrete. Surrey, UK: European Federation of Suppliers of Specialist Construction Chemicals (EFNARC); 2002.
[5] Grünewald S, Walraven JC, Emborg M, Cärlsward J, Hedin C. Test methods for filling ability of SCC. Summary report of workpackage 3.1. Netherlands: Delft University of Technology and Betongindustri; 2004.
[6] Brameshuber W, Uebachs S. Practical experience with the application of self- compacting concrete in Germany. In: Proceedings of the second international symposium on self-compacting concrete. Tokyo, Japan: COMS Engineering Corporation; 2001. p. 687–95.
[7] Bui VK, Montgomery D, Hinczak I, Turner K. Rapid testing method for segregation resistance of self-compacting concrete. Cem Concr Res 2002;32(9):1489–96.
[8] Perez N, Romero H, Hermida G, Cuellar G. Self-compacting concrete, on the search and finding of an optimized design. In: Proceedings of the first North American conference on the design and use of self-consolidating concrete. Illinois, USA: Hanley-Wood, LLC; 2002. p. 101–7.
[9] Khayat KH. Optimization and performance of air-entrained, self-consolidating concrete. ACI Mater J 2000;97(5):526–35.
[10] Kosmatka SH, Kerkhoff B, Panares´e WC, MacLeod NF, McGrath RJ. Design and control of concrete mixtures, 7th ed. Ottawa, Ontario, Canada: Cement Association of Canada; 2002.
[11] Shetty MS. Concrete technology: theory and practice. New Delhi, India: S. Chand and Company Ltd.; 2001.
[12] Hearn N, Hooton RD, Mills RH. Pore structure and permeability. Significance of tests and properties of concrete and concrete-making materials (ASTM STP 169C). Philadelphia, USA: American Society for Testing and Materials. p. 240– 62.
[13] Vanwalleghem H, Blontrock H, Taerwe L. Spalling tests on self-compacting concrete. In: Proceedings of the third international symposium on self- compacting concrete. Bagneux, France: RILEM Publications; 2003. p. 855–62.
[14] Hearn N. On the corrosion of steel reinforcement in concrete. In: Proceedings of the 1st structural specialty conference. Montréal, Quebec: Canadian Society for Civil Engineering; 1996. p. 763–74.

[15] Persson B. A comparison between mechanical properties of self-compacting concrete and the corresponding properties of normal concrete. Cem Concr Res 2001;31(2):193–8.
[16] Bouzoubaâ N, Lachemi M. Self-compacting concrete incorporating high volumes of Class F fly ash: preliminary results. Cem Concr Res 2001;31(3):413–20.
[17] Okamura H, Ozawa K. Self-compactable high-performance concrete in Japan. In: Proceedings of the international workshop on high-performance concrete (ACI SP-159). Farmington Hills, Michigan, USA: American Concrete Institute; 1994. p. 31–44.
[18] Mehta PK, Monteiro PJM. Concrete: microstructure, properties, and materials. 3rd ed. New York, USA: McGraw-Hill Companies, Inc.; 2005.
[19] Salas A, Delvasto S, de Gutierrez RM, Lange D. Comparison of two processes for treating rice husk ash for use in high performance concrete. Cem Concr Res 2009;39(9):773–8.
[20]Mahmud HB, Majuar E, Zain MFM, Hamid NBAA. Mechanical properties and durability of high strength concrete containing rice husk ash. In: Proceedings of the eighth CANMET/ACI international conference on fly ash, silica fume, slag and natural pozzolans in concrete (ACI SP-221). Farmington Hills, Michigan, USA: American Concrete Institute; 2004. p. 751–65.
[21] Zhang MH, Malhotra VM. High-performance concrete incorporating rice husk ash as a supplementary cementing material. ACI Mater J 1996;93(6):629–36.
[22]Maeda N, Wada I, Kawakami M, Ueda T, Pushpalal GKD. Chloride diffusivity of concrete incorporating rice husk ash. In: Proceedings of the fifth CANMET/ACI International conferences on recent advances in concrete technology (ACI SP- 200). Farmington Hills, Michigan, USA: American Concrete Institute; 2001. p. 291–308.
[23]Zhu W, Bartos PJM. Permeation properties of self-compacting concrete. Cem Concr Res 2003;33(6):921–6.
[24]Vegas P. Rice production and marketing. California, USA: Sage V Foods, LLC, Los Angeles; 2008.
[25]Mehta PK. Rice husk ash – a unique supplementary cementing material. In: Proceedings of the CANMET/ACI international symposium on advances in concrete technology. Ottawa, Canada: Canada Communication Group – Publishing; 1992. p. 407–30.
[26] ACI 201.2R-08. Guide to durable concrete. ACI manual of concrete practice (part 1). Farmington Hills, Michigan, USA: American Concrete Institute; 2008.
[27] Khayat KH, Assaad J. Air void stability in self-consolidating concrete. ACI Mater J 2002;99(4):408–16.
[28] Neville AM. Properties of concrete, 4th ed. New York, USA: John Wiley & Sons, Inc.; 1996.
[29] Zhang MH, Lastra R, Malhotra VM. Rice-husk ash paste and concrete: some aspects of hydration and the microstructure of the interfacial zone between the aggregate and paste. Cem Concr Res 1996;26(6):963–77.
[30] De Sensale GR. Strength development of concrete with rice husk ash. Cement Concr Compos 2006;28(2):158–60.
[31] Yu Q, Sawayama K, Sugita S, Shoya M, Isojima Y. The reaction between rice husk ash and Ca(OH)2 solution and the nature of its product. Cem Concr Res 1999;29(1):37–43.
[32] Naik TR, Malhotra VM. The ultrasonic pulse velocity method. CRC handbook on nondestructive testing of concrete. Florida, USA: CRC Press; 1991.