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Performance of rice husk ash produced using a new technology as a mineral admixture in concrete

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Abstract

This article investigates the use of a new technique for the controlled combustion of Egyptian rice husk to mitigate the environmental concerns associated with its uncontrolled burning and provide a supplementary cementing material for the local construction industry. The reactor used provides efficient combustion of rice husk in a short residency time via the suspension of processed particles by jets of a process air stream that is forced though stationary angled blades at high velocity. Investigations on the rice husk ash (RHA) thus produced included oxide analysis, X-ray diffraction, carbon content, grindability, water demand, pozzolanic activity index, surface area, and particle size distribution measurements. In addition, concrete mixtures incorporating various proportions of silica fume (SF) and Egyptian RHA (EG-RHA) produced at different combustion temperatures were made and compared. The workability, superplasticizer and air-entraining admixture requirements, and compressive strength at various ages of these concrete mixtures were evaluated, and their resistance to rapid chloride penetrability and deicing salt surface scaling were examined. Test results indicate that contrary to RHA produced using existing technology, the superplasticizer and air-entraining agent requirements did not increase drastically when the RHA developed in this study was used. Compressive strengths achieved by concrete mixtures incorporating the new RHA exceeded those of concretes containing similar proportions of SF. The resistance to surface scaling of RHA concrete was better than that of concrete containing similar proportions of SF. While the chloride penetrability was substantially decreased by RHA, it remained slightly higher than that achieved by SF concrete.

Keywords: Rice husk ash; Blended cement; High-range water reducer; Compressive strength; Chloride

1. Introduction

Rice production in Egypt is concentrated in a limited agricultural space around the Nile Delta where nearly 8 million tonnes of rice are produced annually, leading to the generation of large volumes of rice by-products. Uncontrolled burning is often considered the most cost-effective disposal method for such by-products. This seasonal and highly localized massive burning generates excessive air pollution that lowers air quality in the neighboring megacity of Cairo, which has become a serious health concern for citizens and authorities. This article investigates the use of a new controlled combustion technology in an attempt to transform Egyptian rice husk from an environmental concern to a useful resource for the production of a highly effective supplementary cementing material.

Research on producing rice husk ash (RHA) that can be used in concrete is not new. In 1973, Mehta [1,2] investigated the effect of pyroprocessing on the pozzolanic reactivity of RHA. Based on his work, Pitt [3] developed a fluidized bed furnace for the controlled combustion of rice husk. It was found that when the temperature of burning and the residency time inside the furnace are controlled, highly pozzolanic RHA could be produced. Since then, many attempts have been made to produce and use pozzolanic RHA in several countries including, among others, China, Japan, India, Guyana, Malaysia, Senegal, Taiwan, and the UK [4–13].

This research intends to develop pozzolanic RHA from Egyptian rice husk; it is the first attempt to use a new technology based on a Torbed reactor in such production.

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This article describes the new combustion technology and the properties of the RHA thus produced and compares its performance in concrete mixtures to that of silica fume (SF) and RHA produced using fluidized bed technology.

2. Combustion of rice husk

The form of silica obtained after combustion of RHA depends on the temperature and duration of combustion of rice husk. Mehta [14] suggested that essentially amorphous silica can be produced by maintaining the combustion temperature below 500 °C under oxidizing conditions for prolonged periods or up to 680 °C with a hold time less than 1 min. However, Yeoh et al. [15] report that RHA can remain in the amorphous form at combustion temperatures of up to 900 °C if the combustion time is less than 1 h, while crystalline silica is produced at 1000 °C with combustion time greater than 5 min. Using X-ray diffraction, Chopra et al. [16] observed that at burning temperatures up to 700 °C, the silica was in an amorphous form. The effect of different burning temperatures and the chemical composition of rice husk (Taiwan RHA) were studied by Hwang and Wu [11]. It was observed that at 400 °C, polysaccharides begin to depolymerize. Above 400 °C, dehydration of sugar units occurs. At 700 °C, the sugar units decompose. At temperatures above 700 °C, unsaturated products react together and form a highly reactive carbonic residue. The X-ray data and chemical analyses of RHA produced under different burning conditions given by Hwang and Wu [11] show that the higher the burning temperature, the greater the percentage of silica in the ash. K, S, Ca, Mg as well as several other components were found to be volatile.

3. New technology for combustion of rice husk

Producing pozzolanic RHA is often made by combustion of rice husk using fluidized beds. A different technique based on a Torbed reactor is used in this study. Torbed reactors have been previously used in several other applications including food, catalyst and mineral processing, gas scrubbing, soil and sediment remediation, and removal of volatiles from solids. A diffuse bed of rice husk particles is held in cyclonic motion in a high-velocity processing air stream (Fig. 1). Centrifugal forces carry the conveyed particles out to the reactor walls where they meet a spinning downward airflow that carries them to the base of the reactor. The small solids load at any time in the reactor allows for precise temperature control, which is essential for the quality of the RHA produced. The advantages of this RHA production technology over circulating fluidized beds include a smaller and more economic reactor, a more thorough processing due to improved retention of particles, no need for external cyclones for separating and reinjecting particles, and the ability of selectively removing particle size ranges from the reactor. A Torbed reactor can operate with gas velocities of 3–12 m/s, while fluidized beds typically operate at 0.1–0.6 m/s. Thus, the cross-sectional area in a Torbed reactor can be 20–30 times smaller than that of a fluidized bed for the same gas flow. A fluidized bed generally operates with a much larger load at any time than a Torbed reactor.

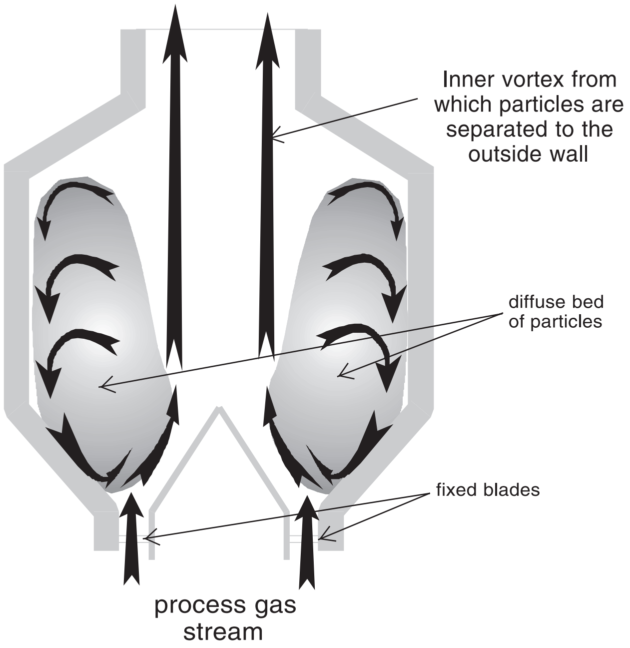

Fig. 1. Illustration of the cyclonic motion of rice husk particles in a Torbed reactor.

4. Materials

Egyptian rice husk tested in a Torbed reactor indicated that pozzolanic RHA having a very low carbon content can be obtained at combustion temperatures between 750 and 850 °C and that a jet of external air on the sidewall of the reactor at locations considered as "hot spots" can increase the surface area of RHA. Therefore, three combustion tests were conducted at 750 and 830 °C plus external jet of air on the sidewall. The resulting RHA from these tests was labeled A, B, and C. A high-quality RHA from the United States (US-RHA), produced using fluidized bed technology, was obtained for comparison. A commercial SF (used here also for comparison with RHA) and ASTM Type I cement were used. The physical and chemical properties of the cement, RHA, and SF are summarized in Table 1. Natural washed gravel with a maximum particle size of 10 mm along with silica sand conforming to ASTM C33 was used in the concrete mixtures. A naphthalene sulfonate superplasticizer with a solid content of 42% was used to achieve the desired workability for all concrete mixtures, and a synthetic detergent air-entraining admixture (AEA) was

Table 1
Physical and chemical properties of cementitious materials used

	Type I cement	RHA-A (750 °C)	RHA-B (830 °C)	RHA-C (750 °C) + air	US-RHA	SF
Physical tests						
Specific gravity	3.17	2.05	2.05	2.05	2.06	2.16
Passing 45 μm (%)	83.9	98.2	97.7	97.9	98.4	97.2
Mean particle size (μm)	13.4	7.15	7.63	7.41	6.8	0.16
Blaine specific surface (m^2/kg)	395					
Nitrogen adsorption (m^2/g)						23.19
Before grinding		13.01	9.99	22.92	24.94	
After grinding		17.96	13.71	23.64	31.25	
f_c' of standard cube (MPa)						
1 day	17.2					
3 days	27.3					
7 days	32.1					
28 days	38.8					
Water requirement (%)		99	95	100	104	114
Pozzolanic activity index (%)						
7 days		88	105	117	114	94
28 days		122	117	144	109	102
Vicat initial setting (min)	92					
Vicat final setting (min)	242					
Mortar air content (%)	7.6					
Chemical analysis						
Silicon oxide (SiO_2)	19.5	94.6	93.7	91.6	89.1	94.0
Aluminum oxide (Al_2O_3)	5.2	0.3	0.3	0.5	0.1	0.1
Ferric oxide (Fe_2O_3)	2.4	0.3	0.2	0.4	0.04	0.1
Calcium oxide (CaO)	61.3	0.4	0.6	0.6	0.6	0.4
Free (CaO)	1.1	–	–	–	–	–
Magnesium oxide (MgO)	0.3	0.3	0.4	0.5	0.5	0.4
Sodium oxide (Na_2O)	1.1	0.2	0.2	0.3	0.2	0.1
Potassium oxide (K_2O)	1.0	1.3	1.4	1.6	1.0	0.9
Equivalent alkalis ($Na_2O + 0.658\ K_2O$)	1.8	1.1	1.2	1.4	0.8	0.7
Phosphorus oxide (P_2O_5)	4.2	0.3	0.4	0.4	0.9	< 0.01
Titanium oxide (TiO_2)	2.00	0.03	0.03	0.04	0.01	0.30
Sulfur trioxide (SO_3)	3.1	–	–	–	–	1.5
Carbon content		1.0	1.4	2.6	5.1	
Loss on ignition	2.5	1.8	2.3	3.7	7.0	2.7
Tricalcium silicate (C_3S)	51					
Dicalcium silicate (C_2S)	18					
Tricalcium aluminate (C_3A)	10					
Tetracalcium aluminoferrite (C_4AF)	7					

used to measure the AEA requirement versus the addition rate of SF and RHA.

5. Experimental methods

Oxide analysis and carbon content measurements for the various RHAs were conducted (Table 1). In addition, X-ray diffraction was used to examine the presence of crystalline silica in each RHA (Fig. 2). After combustion, the various RHA samples were ground using a vibratory ring pulverizer. A laser diffraction particle size analyazer was used to determine the particle size distribution of the cement, SF, and RHA samples. The water requirement and pozzolanic activity index of SF and the various RHA samples were determined as per the ASTM C1250 specifications. In addition, a total of 17 concrete mixtures including a control mixture and incorporating proportions of SF or RHA were made at a constant water-to-cementitious materials ratio (w/cm) of 0.40. The superplasticizer dosage was tailored in each mixture to achieve a slump of 150 ± 20 mm. The proportions of all concrete mixture are shown in Table 2. The fresh concrete properties including slump, air content, and unit weight were determined for each mixture. The AEA dosage required to achieve an air content around 6% versus the replacement rate of cement by RHA and SF was tested. Compressive strength tests at 1, 7, 28, and 56 days and rapid chloride penetrability tests (ASTM C1202) at 28 days were carried out. For some mixtures, concrete slabs 200 × 230 × 75 mm were made and subjected to 50 cycles of freezing–thawing strictly following the ASTM C672 guidelines. The amount of scaled-off material was meas-

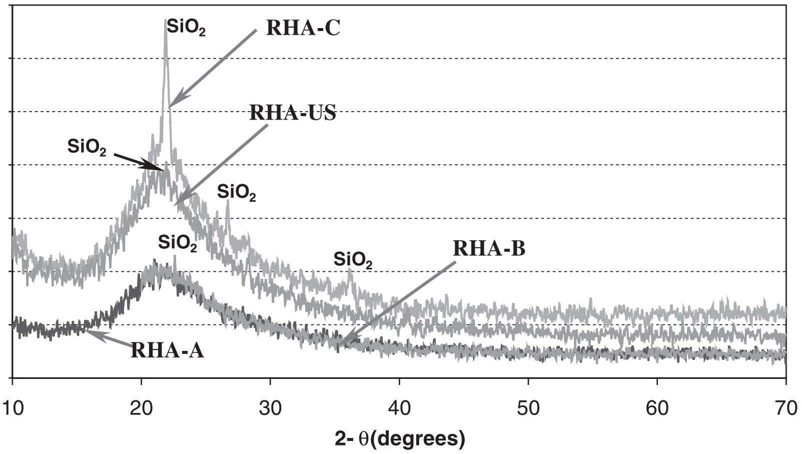

Fig. 2. X-ray diffractograms of various RHA samples.

ured after each five cycles and scaling was given a visual rating.

6. Results and discussion

6.1. Grindability and particle size distribution

Fig. 3 shows the particle size distribution of the cement along with that of nonground and ground RHA samples. The average particle size of the raw RHA sample produced using fluidized bed technology was 107 μm, while that of all RHA samples produced using a Torbed reactor ranged between 44 and 46 μm. This was expected to affect the grinding time required to reach an average particle size of 7 μm, a value considered adequate for this study. Using a vibratory ring pulverizer with a 100-ml capacity, it took about 2.25 times longer for the coarser RHA produced in a fluidized bed to reach the mean particle size. It is not clear why raw RHA produced using a Torbed reactor was finer than that from a fluidized bed, but it could be due to the difference in kinetics of particle motion and heat transfer inside the reactor. The particle size distribution after grinding was very similar for all RHA samples, and therefore the effect of differences in particle size distribution on properties of concrete incorporating the various RHAs should be minimal. The figure also shows that ground RHA is finer than cement and should be expected to play not only a pozzolanic role, but also a microfiller effect to enhance the particle packing density of concrete.

6.2. Surface area and carbon content

Table 1 shows the surface area before and after grinding and the total carbon content (graphitic and organic) for the various RHA samples. The surface area after grinding of

Table 2
Mixture proportions, slump, and density of the various concrete mixtures

Mixture	Cement (kg/m^3)	Fine aggregate (kg/m^3)	Coarse aggregate (kg/m^3)	Water (kg/m^3)	RHA (kg/m^3)	SF (kg/m^3)	US-RHA (kg/m^3)	HRWR[a] (l)	Slump (mm)	Density (kg/m^3)
Reference mix	380	760	1140	152	–	–	–	1.5	170	2400
EG-RHA 7.5% (A)	352	745	1140	152	29	–	–	2	165	2440
EG-RHA 7.5% (B)	352	745	1140	152	29	–	–	2	160	2405
EG-RHA 7.5% (C)	352	745	1140	152	29	–	–	2.5	150	2420
EG-RHA 10% (A)	342	740	1140	152	38	–	–	2	175	2390
EG-RHA 10% (B)	342	740	1140	152	38	–	–	1.5	150	2465
EG-RHA 10% (C)	342	740	1140	152	38	–	–	2	160	2405
EG RHA 12.5% (A)	333	735	1140	152	48	–	–	2	145	2430
EG-RHA 12.5% (B)	333	735	1140	152	48	–	–	2	170	2400
EG-RHA 12.5% (C)	333	735	1140	152	48	–	–	1.75	130	2390
SF 7.5%	352	750	1140	152	–	29	–	2	170	2410
SF 10%	342	745	1140	152	–	38	–	3	145	2400
SF 12.5%	333	740	1140	152	–	48	–	3.5	155	2445
US-RHA 7.5%	352	745	1140	152	–	–	29	2	130	2415
US-RHA 10%	342	740	1140	152	–	–	38	2.5	145	2410
US-RHA 12.5%	333	735	1140	152	–	–	48	3	160	2390
Raw US-RHA 7.5%	352	745	1140	152	–	–	29	3.3	160	2415
Raw US-RHA 10%	342	745	1140	152	–	–	38	4	145	2415

[a] HRWR=High-range water reducing admixture.

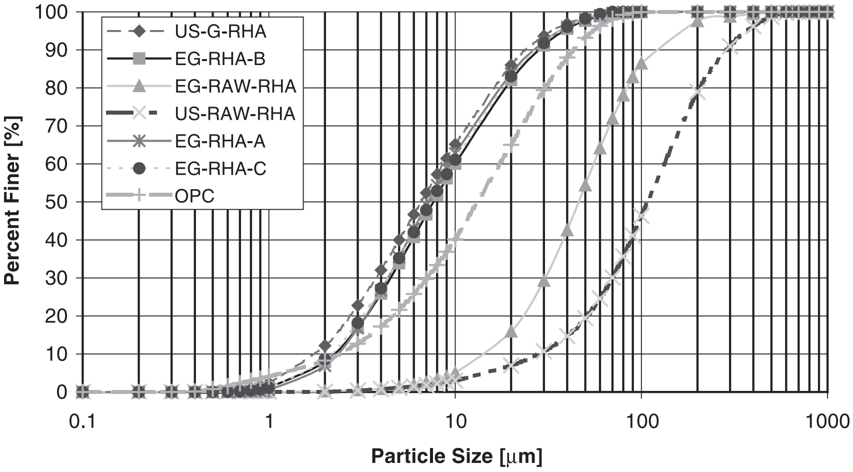

Fig. 3. Particle size distribution of cement, raw RHA, and ground RHA (EG and US indicate RHA from Egypt and the United States, respectively).

RHA samples produced using a Torbed reactor ranged between 13 and 24 m^2/g, while it was around 31 m^2/g for RHA produced using a fluidized bed. The total carbon content ranged between 1% and 2.6% for RHA produced using a Torbed reactor, while it reached 5.1% in RHA produced in a fluidized bed. Malhotra [17] suggested that the surface area of incinerated rice husk is 60–100 m^2/g when measured using nitrogen adsorption. The values measured in this study for all RHA samples are much lower than this range. Bradley et al. [18] found that with oxidation, considerable increases in microporosity can be achieved. According to Rouquerol et al. [19], carbon produced by controlled pyrolysis or combustion from a variety of organic precursors can have very high surface area in excess of 2000 m^2/g. By simple calculation, assuming that an RHA having a surface area of 20 m^2/g contains 5% of microporous carbon that has a surface area of 1000 m^2/g, the resulting surface area of the blend will be 69 m^2/g. Thus, the difference in surface area between RHA produced in a Torbed reactor and that produced in a fluidized bed may be due the difference in carbon content.

6.3. X-ray diffraction and oxide analysis

Fig. 2 shows X-ray diffractograms for the various RHA samples. There was no significant difference between results for RHA-A and -B produced at 750 and 830 °C, respectively, in a Torbed reactor. Both appear mainly amorphous. Only very small peaks that could be identified as crystalline silica were identified. On the other hand, RHA-C, also produced in a Torbed reactor at 830 °C with a jet of air stream on the reactor sidewall, had a very distinct peak corresponding to crystalline silica, and the reason for this behavior is not well understood. The RHA produced using a fluidized bed had more distinct crystalline silica peaks compared to RHA-A and -B, but less distinct than RHA-C. The oxide analysis for the various RHA samples is summarized in Table 1. The silicon oxide (SiO_2) content varied between 91.6% and 94.7% for RHA produced using a Torbed reactor and was 89% for RHA produced using a fluidized bed. Another significant difference is that the Egyptian RHA (EG-RHA) contained more alkalis than the US-RHA did.

6.4. Water demand and pozzolanic activity index

The water requirement for all RHA samples was lower than 100%, while it was about 114% for SF although some of the RHAs had higher surface area than SF. The pozzolanic activity index at 7 and 28 days for SF and the various RHA samples is shown in Table 1. At 7 days, it ranged from 87% to 117% for the Torbed RHA, while it was 114% and 94% for the fluidized bed RHA and SF, respectively. At 28 days, the pozzolanic activity index ranged between 117% and 144% for the Torbed RHA while it measured 109% and 102% for the fluidized bed RHA and SF, respectively. The reason for the low pozzolanic activity index values of SF is perhaps the high water requirement for the SF mortar mixture compared to the RHA mixtures (no superplasticizer was used as per ASTM C1240), which resulted in a higher w/cm ratio. The higher pozzolanic activity index for the EG-RHA, although it had a lower surface area compared to the US-RHA, supports the earlier suggestion that the higher carbon content in the US-RHA may be responsible for its higher surface area.

6.5. Air-entraining admixture and superplasticizer requirements

The concrete mixtures investigated are non-air entrained because it is not a common practice to use air entrainment in Egypt. However, the AEA required to achieve approximately 6% of entrained air in concrete mixtures versus the replacement rate of cement by SF and two RHA samples was measured and results are shown in Fig. 4. It can be observed that the AEA requirement increased for all mineral

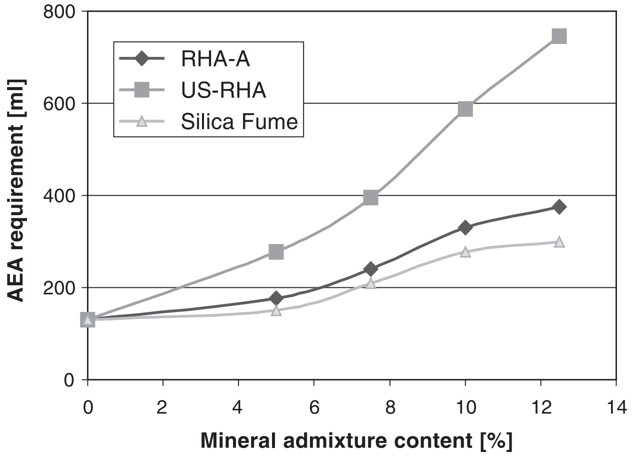

Fig. 4. AEA requirement versus RHA and SF addition rate.

admixtures with increasing replacement rate. However, the AEA requirement for concrete incorporating fluidized bed RHA was higher than that of RHA produced using a Torbed reactor, likely due to its higher carbon content. Moreover, the AEA requirement for all RHA concrete mixtures was higher than that of SF concrete mixtures. Comparable results were observed by Zhang and Malhotra [12]. In non-air-entrained concrete mixtures, the superplasticizer requirement to achieve a 150 ± 20-mm slump increased in RHA concrete mixtures compared to the reference mixture. However, contrary to the results of Zhang and Malhotra [12], the superplasticizer requirement for concrete mixtures incorporating SF was higher than that of concrete mixtures incorporating similar proportions of RHA. Comparable results were obtained by Bouzoubaâ and Fournier [13].

6.6. Compressive strength

Compressive strength results for the various concrete mixtures at 1, 7, 28, and 56 days are shown in Fig. 5. Substituting 7.5% of cement with RHA-A, -B, or -C increased the 1-day compressive strength. RHA-C achieved the highest 1-day strength improvement. For a 10% replacement level, only RHA-C increased the strength significantly. At 12.5% replacement rate, RHA-A and -C achieved slight

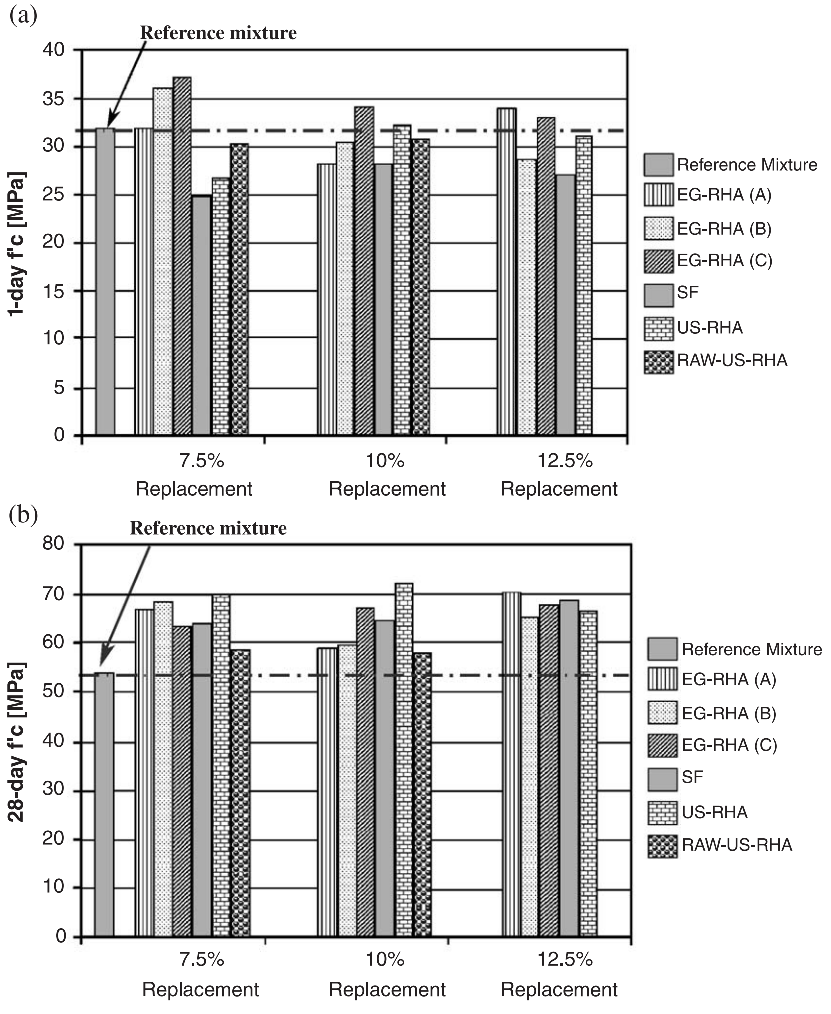

Fig. 5. Compressive strength at (a) 1 and (b) 28 days for the various concrete mixtures (EG and US indicate RHA from Egypt and the United States, respectively).

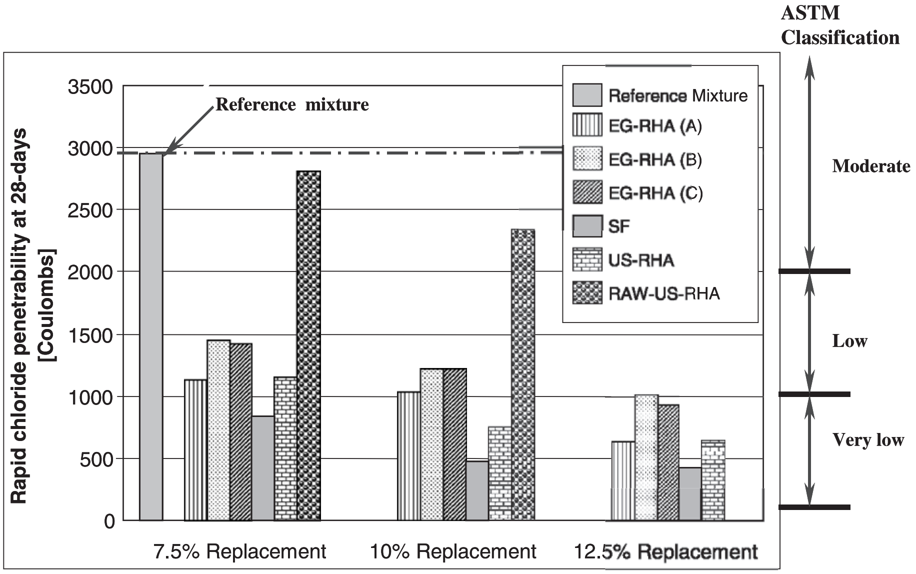

Fig. 6. Rapid chloride penetrability at 28 days for various concrete mixtures (EG and US indicate RHA from Egypt and the United States, respectively).

improvements of the 1-day compressive strength. The US-RHA, although having the highest surface area of all RHA samples, did not enhance the 1-day strength at all replacement levels. Likewise, SF decreased the 1-day strength at all replacement levels. At 28 days, the strength of all mixtures incorporating RHA and SF additions outperformed that of the reference mixture. At 56 days, using 7.5%, 10%, and 12.5% cement replacement with EG-RHA increased the compressive strength of concrete by up to 20%, 27%, and 40%, respectively, depending on the type of RHA and the addition rate. Similar proportions of US-RHA and SF increased the 56-day strength by up to 27% and 22%, respectively. Based on strength results alone, this study shows that good quality RHA can match and even outperform strength enhancements in concrete achieved by SF, and this is even more significant at early ages. Fig. 5 shows that nonground US-RHA enhanced compressive strength only at 28 and 56 days. However, the superplasticizer requirement to achieve a 150 ± 20-mm slump for concrete mixtures incorporating nonground RHA increased significantly, which makes its use difficult to justify economically.

6.7. Rapid chloride penetrability

Rapid chloride penetrability results are illustrated in Fig. 6 along with the ASTM C1202 classification ranges. It is shown that proportions of nonground RHA did not significantly change the rapid chloride penetrability classification of concrete. However, using finely ground RHA reduced the rapid chloride penetrability of concrete from a moderate rating to low or very low ratings depending on the type and addition level of RHA. Such reductions are comparable to those achieved by SF. Egyptian and Middle Eastern concrete infrastructure performs in some of the most hostile environments with respect to corrosion and salt attack. Therefore, RHA would not only contribute to reducing the environmental impact of uncontrolled burning or rice milling by-products but would also enhance the durability of the local concrete infrastructure. It can also be observed in Fig. 6 that although the US-RHA had about 73% higher surface area compared to EG-RHA-A, the latter outperformed it at 12.5% addition rate in terms of compressive strength at all ages and in resisting chloride penetrability. This supports the hypothesis stated earlier that published surface area values of RHA may be artificially too high due to the high content of microporous carbon (5.1% in US-RHA versus 1.1% in RHA-A).

6.8. Surface scaling due to deicing salts

Deicing salt surface scaling tests were conducted for the reference mixture along with mixtures incorporating 10% of RHA-A (selected because it achieved good performance in chloride penetrability tests), US-RHA, and SF as per ASTM C672 guidelines. Results are summarized in Table 3. Visual rating of the performance of slab specimens after 50 cycles of freezing–thawing showed that all RHA concrete specimens performed generally similar to the reference concrete mixture but somewhat better than SF

Table 3
Results of deicing salt surface scaling tests

Mixture	Visual rating ASTM C672	Total scaling residue (kg/m^2)
Control (100% ordinary Portland cement)	2	0.40
RHA-A 10%	2	0.55
US-RHA 10%	2	0.60
SF 10%	3	0.85

concrete specimens. Only the SF concrete specimens showed some coarse aggregate exposure. The mass of scaled-off material was generally lower than 0.8 g/m^2, a value used in the Ontario Provincial standard specifications as a criterion to evaluate the resistance of concrete to deicing salt scaling. These results are in agreement with those of Zhang and Malhotra [12].

7. Conclusions

A new technology for the production of RHA based on a Torbed reactor allowed producing highly reactive RHA with much lower carbon content than that of RHA produced using fluidized beds. The technique was applied to rice husk from Egypt, and the performance of the resulting RHA was compared to those of SF and RHA produced in the United States using fluidized bed technology. The RHA produced using the new technique required less grinding time than that produced in a fluidized bed and did not substantially increase the water demand and the superplasticizer requirement, which is an advantage compared to SF. The AEA requirement for the RHA concrete was higher than that of SF concrete but much lower than that of typical fluidized bed RHA concrete. Moreover, RHA had a pozzolanic activity index as high as 117% at 7 days and 144% at 28 days.

Depending on the addition rate, RHA enhanced the compressive strength of concrete by up to 40% at 56 days and was superior to SF in this regard. Moreover, RHA reduced the rapid chloride penetrability of concrete from a moderate to a low or very low ASTM C1202 classification depending on the addition rate, which was comparable to improvements imparted by SF. RHA concrete was slightly more efficient than SF concrete in resisting surface scaling due to deicing salts. Considering the availability of rice husk worldwide, this study shows that economic technology can be used in rice-producing countries to produce a highly effective supplementary cementing material and reduce the environmental impact of uncontrolled burning of rice by-products.

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